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THE UNIVERSITY OF ALBERTA

ICE JAM ANALYSIS IN A COMPLEX REACH: A CASE STUDY

BY

STEPHEN J. STANLEY

A THESIS
SUBMITTED TO THE FACULTY OF GRADUATE STUDIES AND RESEARCH IN PARTIAL
FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE
OF MASTER OF SCIENCE

DEPARTMENT OF CIVIL ENGINEERING

EDMONTON, ALBERTA
FALL, 1988

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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research for acceptance, a thesis entitled ICE JAM ANALYSIS IN A COMPLEX REACH: A CASE STUDY submitted by STEPHEN J. STANLEY in partial fulfilment of the requirements for the degree of MASTER OF SCIENCE in CIVIL ENGINEERING.

SUPERVISOR

DATE: 11 Oct 88

This thesis is dedicated to my wife, Jennifer. She provided inspiration and showed unlimited patients during this study.

Abstract

This thesis is a case study for which ice jam flooding is analyzed for a site which contains complex morphology. The site is the Town of Hay River which is situated in the delta of the Hay River as it enters the south side of Great Slave Lake. In delta region the river is very non-uniform, with the river splitting into a number of sub-channels. The complex morphology of the site provides a good test for much of the existing ice jam theories. Included in the study was an analysis of the severity of the ice jam flooding problem at Hay River, documentation of the ice regime for the river, use of a numerical model to calculate ice jam water level profiles, and development of an ice jam flood forecasting algorithm.

To quantitatively assess the severity of flooding in Hay River a probability analysis was done. Because of the lack of standard hydrometric data and the complex morphology, the analysis had to rely almost completely on local historical data.

The documentation of two break-ups at Hay River provided the data needed to calibrate a model to obtain ice jam water level profiles.

Because of the very non-uniform channels and the need to estimate water levels in the developing portions of the jam, the commonly used models based on equilibrium theory could not be used. Instead a recently-developed model was used that

could calculate the water surface profiles over the entire length of the jam in a non-prismatic channel. Although developed for this purpose it had not been applied in such a channel before. The calculated profiles from the model were very close to those measured.

The results of the model were the basis for the flood forecasting algorithm. The water levels estimated from the model were further refined to allow for the influence of surges released by ice jam failure upstream. The latter component was based on an empirical analysis of hydrometric antecedents.

ACKNOWLEDGEMENTS

The author would like to sincerely thank Dr. R. Gerard for his support, advice and encouragement throughout the course of this study. It is his enthusiastic interest in water resources that is apparent in his courses that first interested the author in further study in this field.

The author greatly appreciates the help of graduate students D. Williamson and Joe Greoneveld for their help with the field work and running of the computer model. The assistance of S. Lovell and S. Lodewyk with the preparation of equipment of the field work is also appreciated.

The Town of Hay River has provided substantial support. Mr. B. Latham of INAC has provided patient liason between the parties. The encouragement and assistance of residents of Hay River, particularly Mr. 'Red' McBryan, Mr. J. Pollard, Mr. L. Brunes, and Dr. D. Harrison, is especially appreciated.

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1 Introduction

Ice jams are an important feature of hydrology in cold regions. In many cases water levels produced by ice jams far exceed those of extreme open water floods. Ice jam floods have resulted in a great deal of property damage and, on occasion, loss of life. On the Saint John River in New Brunswick, flood damages due to ice jams in 1987 were estimated to be about $30,000,000. Normally New Brunswick averages about $5,000,000 in flood damage per year and about 70 percent of this can be attributed to ice related flood events (Humes and Dublin, 1988). The above figures only include a small fraction of the world's area where ice jam flooding is a problem. Even though ice jam flooding causes a significant portion of the annual flood damage in Canada, much is still to be understood about ice jam processes.

In nature ice jam formation is not unusual. However, ice jams tend to be very brief and their influence quite local. Therefore if the location is not near a settlement or an installation, the ice jam often goes unnoticed. This has resulted in a general lack of quantitative data on ice jam behavior, which in turn has held back the development of the understanding of ice jam processes. The lack of understanding and the complexities involved in ice jam hydraulics has resulted in ice jam effects being ignored in many flood risk assessments. Consequently flood risk assessments have been produced that ignore the very process that results in many of the extreme flood events at the site.

This present work is a case study of ice jam processes at Hay River, NWT. The site features very complex morphology and severe flooding by ice jams which form at the mouth of the river as it enters Great Slave Lake.

1.1 Purpose and Scope

This study was initiated in response to the severe flooding that occurred in Hay River in 1985. Flood levels reached in that year were over 1 m above the defined 1 percent flood level that had been declared the previous year. This prompted government officials to authorize an in depth study of ice jam flooding in Hay River.

As mentioned earlier, few past flood risk assessments have taken proper account of ice jam floods. This was the case in Hay River. It was therefore necessary to develop a new flood risk assessment. The 1985 flood also highlighted the need for a flood forecasting procedure. The development of these two tasks was the focus of this study.

1.2 Ice Jam Features

A brief overview of ice jam features is presented to provide background to the terms used in the description of ice jams. A more detailed review of ice jam mechanics is included in Chapter 6.

An ice jam can most simply be described as an accumulation of ice floes or fragments in a river. They have been described by Uzuner and Kennedy (1976) as "at best, chaotic, disorderly, untidy affairs". In short, a complex phenomenon.

Ice jams are broadly classified on the basis of the circumstance under which they are formed. They can form at freeze-up, spring break-up or, in the case of a mid-winter thaw or rain, in winter. Freeze-up jams are generally less severe than winter or break-up jams, as they are composed of relatively small ice floes, usually frazil slush or pans and are normally associated with low discharges. Mid-winter and break-up jams can be much more severe as they can be composed of solid ice floes several metres in dimensions. and can be associated with high discharge. The remainder of this thesis is concerned only with break-up jams.

Break-up of a river can vary from a thermal break-up, where the ice melts in place, to the dramatic dynamic break-up. Severe ice jams are normally associated with the latter. In the dynamic break-up the still competent ice cover is forcibly broken out by the passage of a surge of water. The fragmented ice floes created during the dynamic break-up are transported downstream until the surge in attenuated or they meet some obstruction . The obstruction is normally a more-than-usually resistant portion of solid ice cover. An ice jam develops as the floes accumulate upstream of the obstruction. This accumulation will cause a local rise in water levels. The rise is partly the result of the increased roughness of the fragmented ice and partly due to the draft of the submerged ice.

Figure 1.1 details the various components of an hypothetical ice jam. The major components are the toe, which is the downstream portion of the jam, the equilibrium section, which has relatively constant thickness, and the head, where the ice floes accumulate. Between each of these components is a transition section.

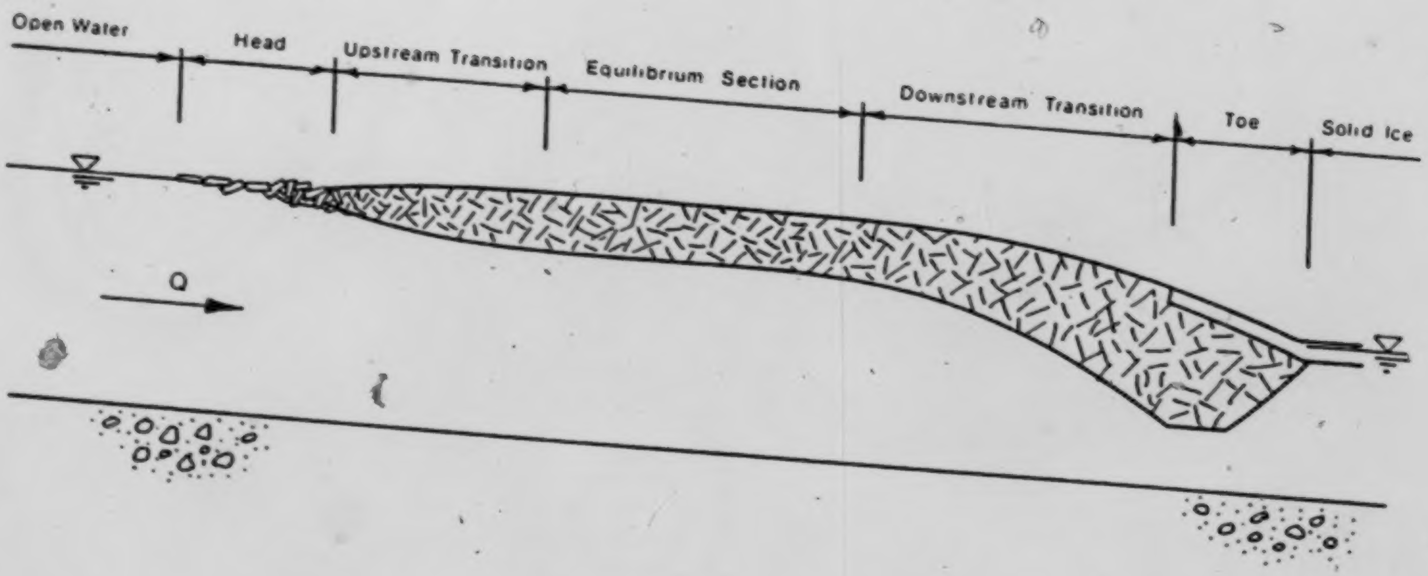

Open Water
Head
Upstream Transition
Equilibrium Section
Downstream Transition
Toe
Solid Ice
Q

Figure 1.1 Hypothetical ice jam profile (modified from Flato and Gerard ,1986)

2. THE HAY RIVER AND THE TOWN OF HAY RIVER

2.1 General description of the Hay River catchment

The Hay River catchment covers some 48,100 km^2, portions of which are located in two provinces (British Columbia and Alberta) and the Northwest Territories (NWT), as shown in Figure 2.1. Its approximate orientation is southwest-northeast, with the source in the southwest and the mouth discharging on the south-west shore of Great Slave Lake in the NWT. The majority of the basin lies within Alberta, with only 19.5 percent in B.C. and 6.5 percent in the N.W.T.

The entire basin is located in the northwestern portion of the Great Central Plains (Douglas, 1970). It lies in the southern portion of the zone of discontinuous permafrost with the southern regions containing sporadic areas of permafrost which becomes more abundant in the northern regions of the catchment. The Town of Hay River is situated on permanently frozen ground which has been measured to be 10m thick with an active layer of 2 to 3 m.

Within the catchment there are three distinct regions. These are the Chinchaga River Basin, the Upper Hay River basin and the Lower Hay River basin. The Chinchaga River basin covers 11,000 km^2 and contains the highest elevations in the catchment. These are at the far south-east corner of the basin where the Halverson Ridge has an elevation of 1200

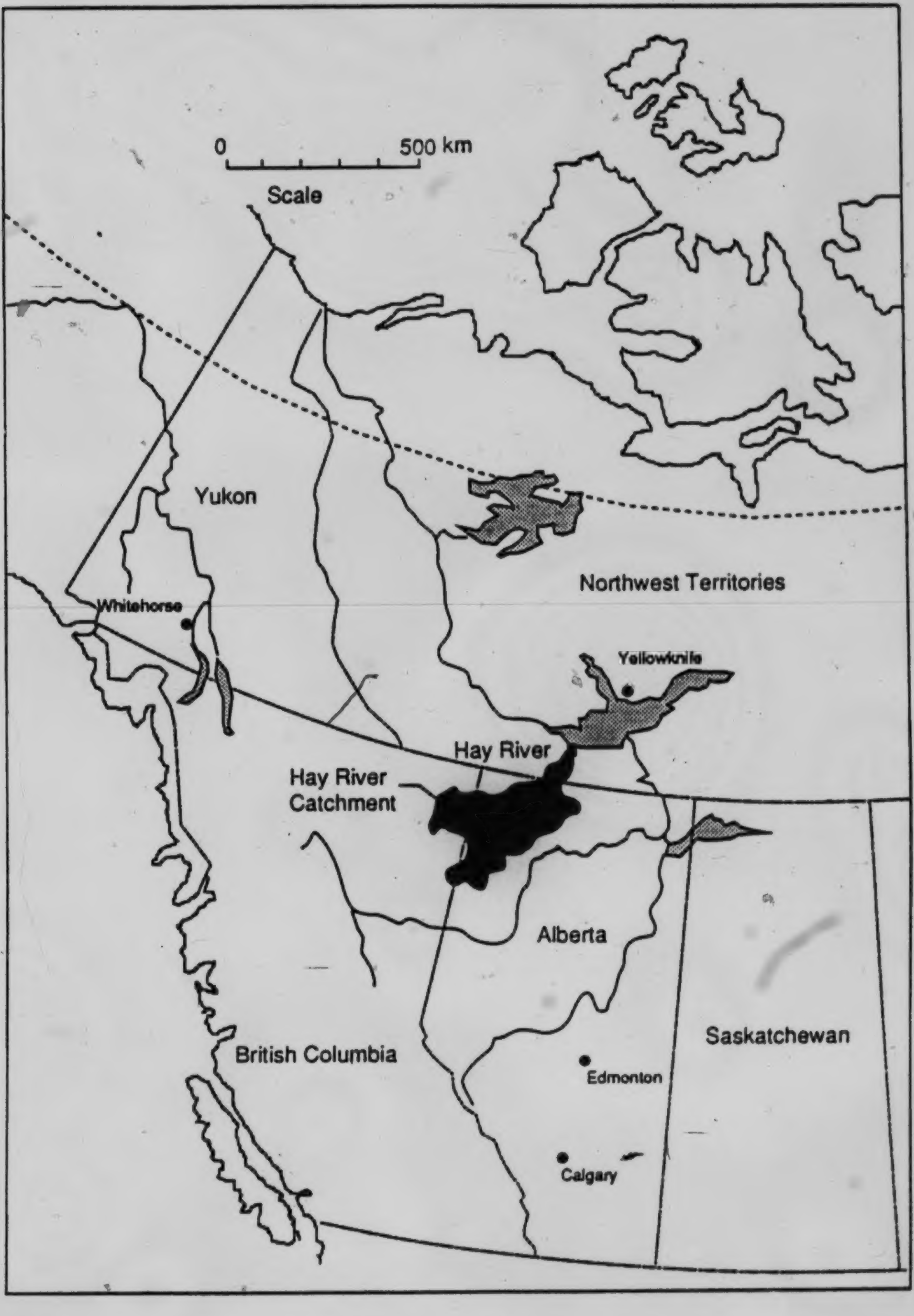

0
500 km
Scale
Yukon
Northwest Territories
Whitehorse
Yellowknife
Hay River
Hay River Catchment
Alberta
British Columbia
Saskatchewan
Edmonton
Calgary

Figure 2.1 Catchment location map

m, as is shown in Figure 2.2. In the Chinchaga basin over 60 percent of the total area lies above an elevation of 610 m (UMA, 1979). This upper area contains vegetation of mostly spruce and lodgepole pine (GNWT, 1984), as shown in Figure 2.3. The lower section of the Chinchaga basin can be described as flat plains, as it is part of the Fort Nelson Lowlands. This section has a gradual downward slope to the north, from the upper hills to the confluence with the Hay River.

The Upper Hay River Basin covers about 20,000 km^2. This sub-basin is much lower than the Chinchaga basin as only 15% of the basin area lies above 610 m. The high areas contain spruce and lodgepole pine but the majority of this sub-basin is covered with blackspruce and aspen. The major feature of the lower area is Zama Lake which is in a low lying swampy area and the only real storage in the Hay River system.

The Lower Hay River Basin covers 17,000 km^2. It extends northward between the Cameron Hills (elevation 750 m) to the west and the Caribou Mountains (elevation 900 m) to the east. The valley is wide and characterized by low - relief, muskeg-ridden terrain. It has a gradual northward slope to two falls at the northern end of the basin. Alexandra Falls (km 1034.95) is the first and largest of the two falls and drops 33 m. Louise Falls (km 1037.12) drops 15 m. The mouth of the river lies 75 km beyond this on the south shore of Great Slave Lake.

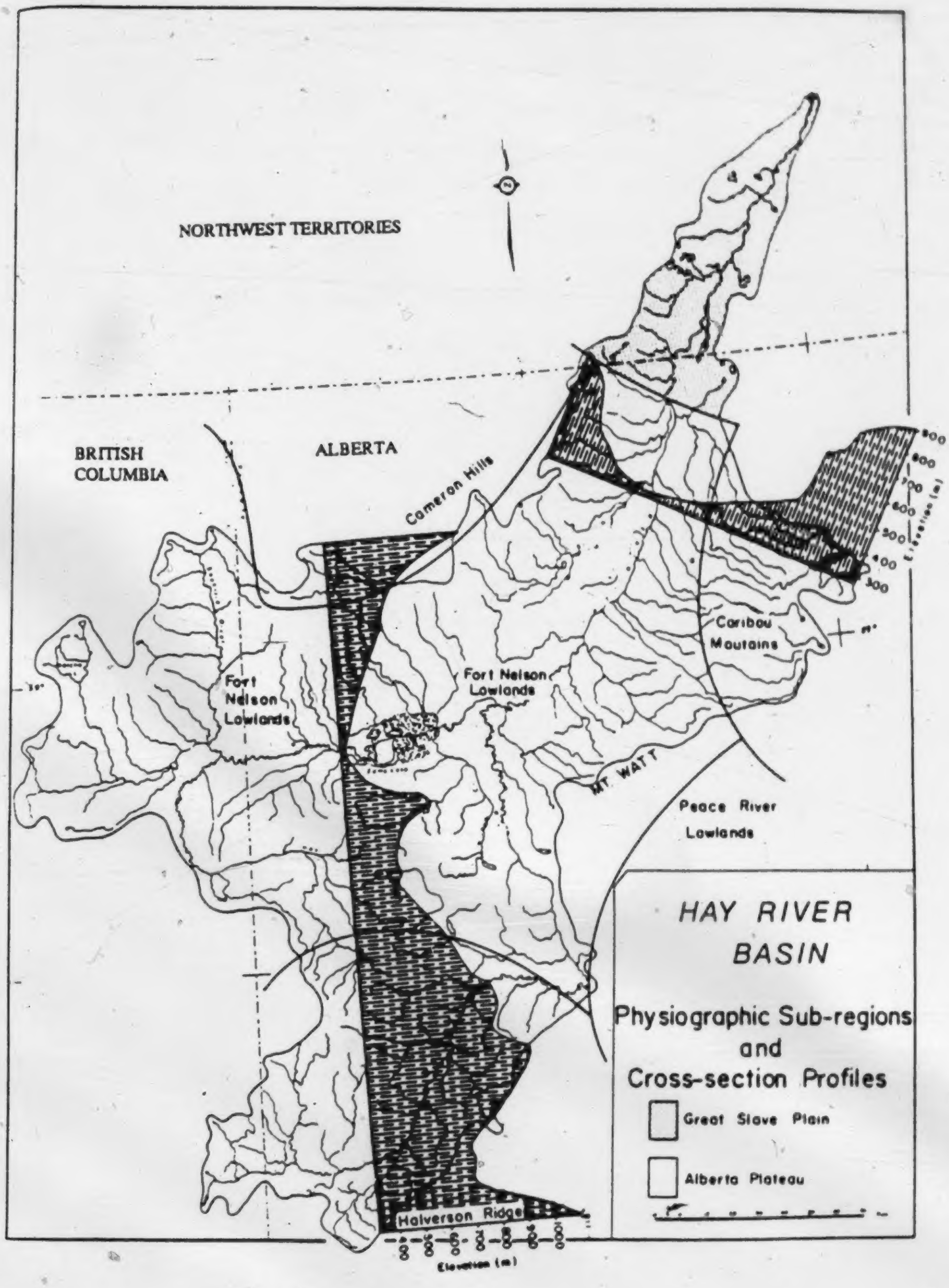

NORTHWEST TERRITORIES
BRITISH COLUMBIA
ALBERTA
Cameron Hills
Fort Nelson Lowlands
Fort Nelson Lowlands
Caribou Moutains
MT. WATT
Peace River Lowlands
Halverson Ridge
Elevation (m)
800
700
600
500
400
300
HAY RIVER BASIN
Physiographic Sub-regions and Cross-section Profiles
Great Slave Plain
Alberta Plateau

Figure 2.2 Hay River basin topography (modified from GNWT, 1984).

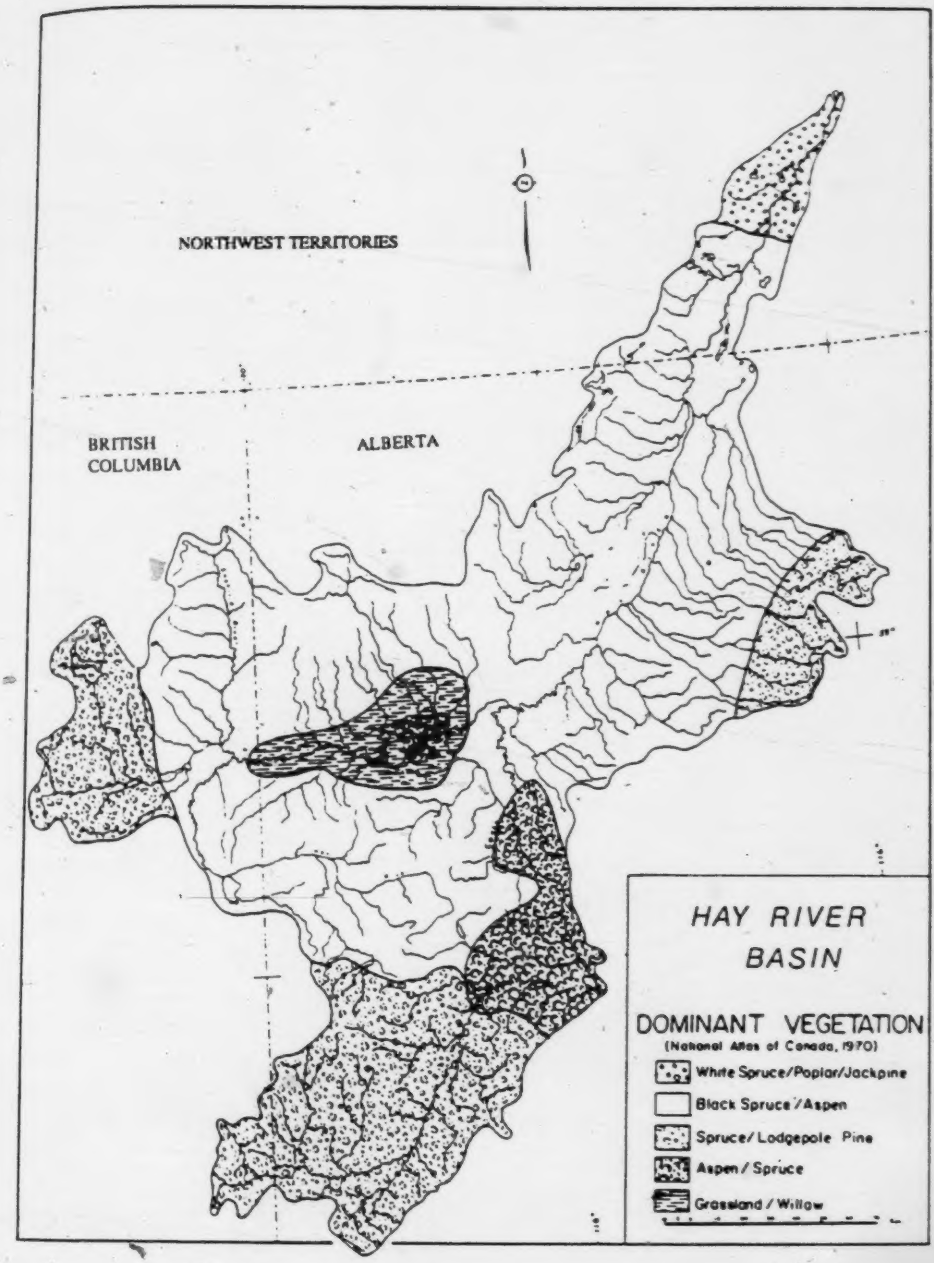

NORTHWEST TERRITORIES
BRITISH COLUMBIA
ALBERTA
HAY RIVER BASIN
DOMINANT VEGETATION
(National Atlas of Canada, 1970)
White Spruce/Poplar/Jackpine
Black Spruce/Aspen
Spruce/Lodgepole Pine
Aspen/Spruce
Grassland/Willow

Figure 2.3 Hay River basin dominant vegetation (modified from GNWT, 1984).

There are many tributaries along the river. The most prominent is the Chinchaga River (km 709.33), which is about the same size as the Hay River at its confluence with the Hay River. Other major tributaries are the Steen River (km 880.72) and the Meander River (km 822.84). (To provide unambiguous and convenient reference to positions along the river, the distances given are measured from the river source at coordinates UTM 311280 / 6379670 and were calculated from a digitized plan of the river as described in Appendix A.)

2.2 River morphology

A complete profile of the Hay River is shown in Figure 2.4. The upper portion of the river is relatively steep with an average slope of 0.001. At about km 400 this slope reduces to about 0.00045. As the river progresses downstream the slope gradually lessens, with the average slope decreasing to 0.0001 for the 200 km above the falls (km 800 to km 1000). In these areas of lesser slope (km 400 to km 1000) the river is meandering in a wide valley.

The reach of most interest in the study is from below the falls to Great Slave Lake. This includes 78 km of river that contains a wide variety of river morphology. Directly below Louise Falls the river is confined between steep and high bedrock walls (approximately 25 m in height). In this area the river is very steep with an average slope of 0.003

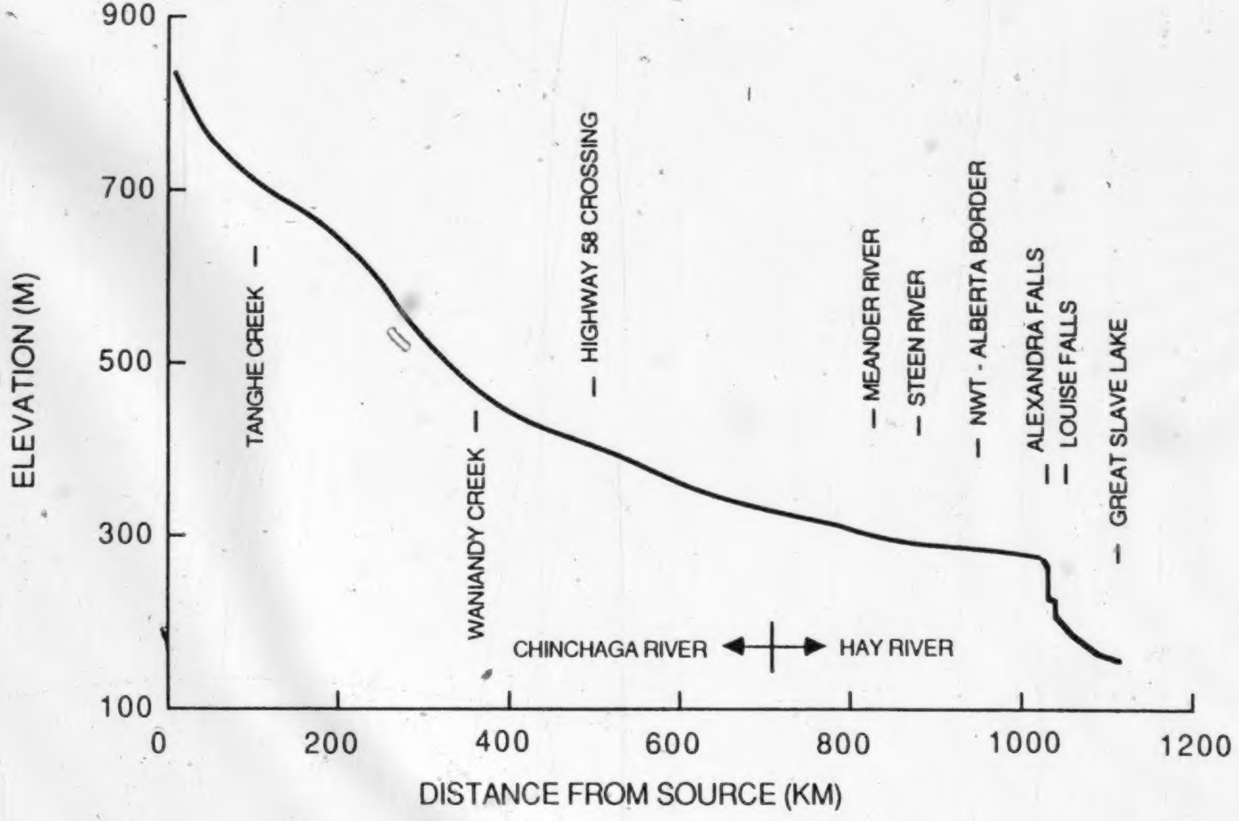


Figure 2.4 Profile of the Hay River.

for the 10 km directly below the falls. Alexandra Falls and the river below Louise Falls are shown in Figure 2.5 and 2.6.

The height of the river banks slowly decrease as the river approaches the lake. By km 1095, about 20 km upstream of the lake, the banks are about 5 to 10 m in height with gradual slopes to the river. The banks remain at approximately this height right to where the river splits into two main channels, the East and West Channels, at the delta. Consequently the river above the split has little or no chance of flooding, even during severe break-up events. Below the split the banks decrease in height substantially, with many locations having banks only 1 to 2 m above the average summer flow stage.

The delta, below the split, is a relatively flat low-lying area characterized by numerous channels, both active and abandoned, and can be subject to severe flooding during the spring runoff period. As the river enters the delta region the slope decreases dramatically, with the average slope in the area of the split only being 0.0001. The split of the river into the East and West Channels forms the largest of the delta islands, called Vale Island. The delta region of the Hay River in shown in Figures 2.7 and 2.8. The East Channel is the main channel and normally carries about two-thirds to three-quarters of the discharge. The West Channel can be thought of as a high level by-pass channel as its thalweg is much higher than that of the East Channel. The West Channel will actually freeze to the bottom in its

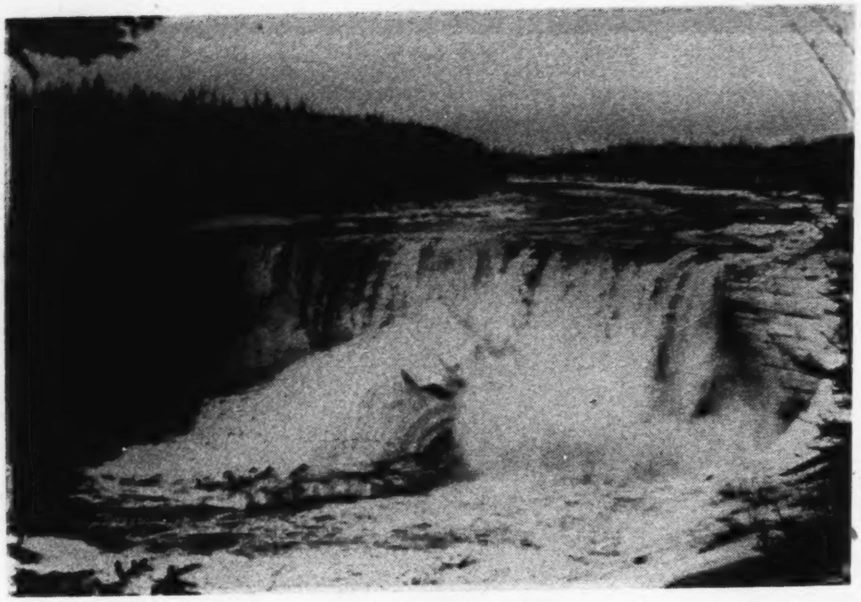


Figure 2.5 Alexandra Falls, break-up 1987.

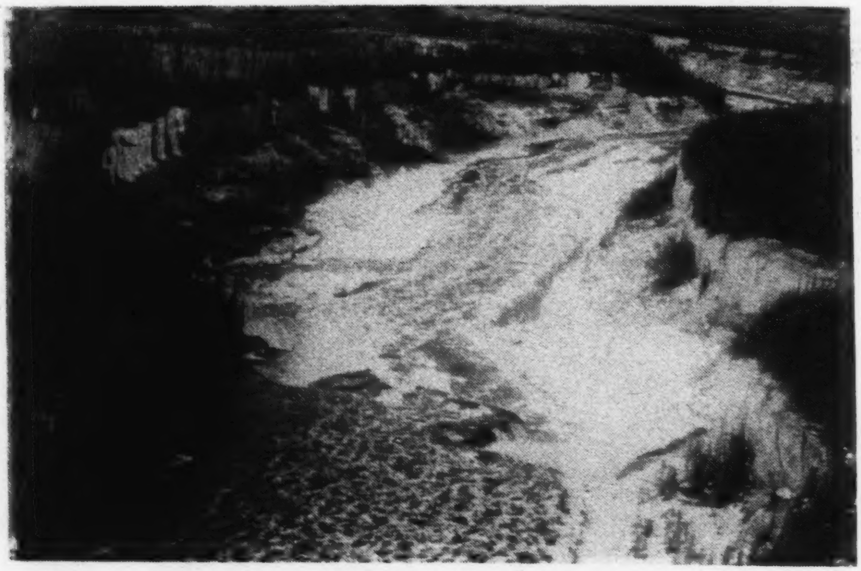


Figure 2.6 Looking downstream below Louise Falls.

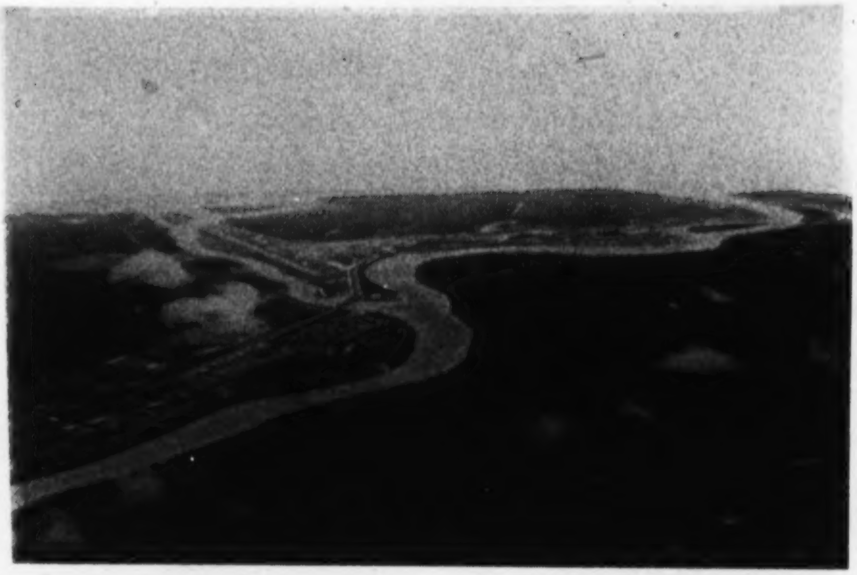


Figure 2.7 The Hay River delta, looking downstream towards Great Slave Lake.

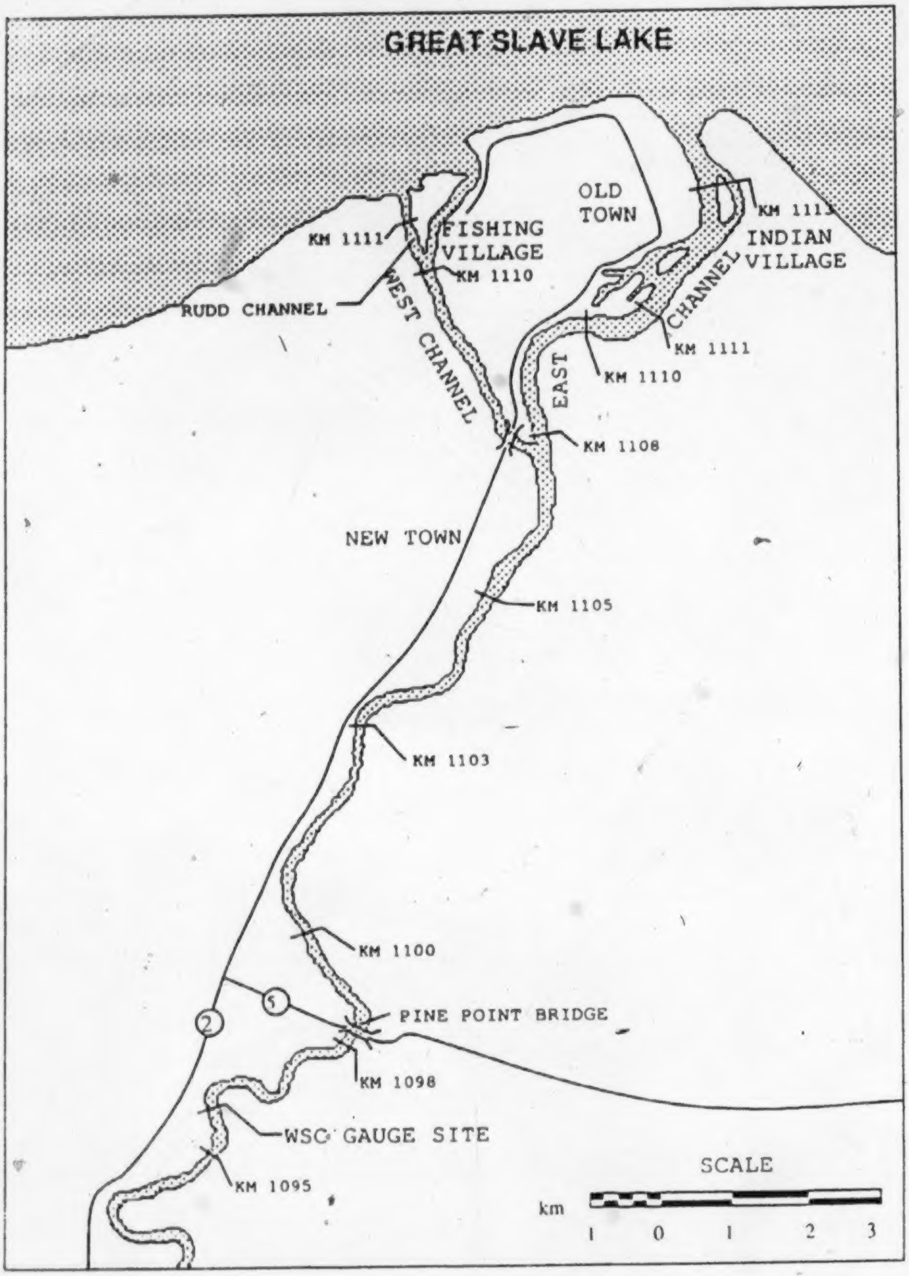

GREAT SLAVE LAKE
OLD TOWN
FISHING VILLAGE
INDIAN VILLAGE
KM 1111
KM 1110
KM 1113
RUDD CHANNEL
WEST CHANNEL
EAST CHANNEL
KM 1111
KM 1110
KM 1108
NEW TOWN
KM 1105
KM 1103
KM 1100
PINE POINT BRIDGE
2
5
KM 1098
WSC GAUGE SITE
KM 1095
SCALE
km
1
0
1
2
3

Figure 2.8 Location plan, Town of Hay River, N.W.T.

upper reaches during the river and during very low flows in the summer can became dry. The thalweg profiles of the delta channels are given in Figure 2.9.

2.3 Discharge

The annual daily mean hydrograph for Hay River at Hay River is given in Figure 2.10. As shown the annual variation in the stream flow is considerable, eg. at the Town of Hay River the mean low flow is 4 m^3/s and the mean peak flow is 450 m^3/s. Much of this variation is the result of the long winters which eliminate almost all sources of water during this period. With little on-stream storage in the system flows decrease dramatically by late winter.

The discharge hydrograph is characterized by a rapid rise in the hydrograph at the commencement of spring thaw. A somewhat unique feature of the hydrograph at Hay River is that the annual peak flow normally coincides with the spring break-up process.

At present there are nine Water Survey of Canada hydrometric gauging stations in the basin. The oldest is Hay River at Hay River, which began operation in 1964. The newest is that for the Hay River at the Alberta/NWT border, which began in 1987. Table 2.1 lists the hydrometric stations and their drainage areas.

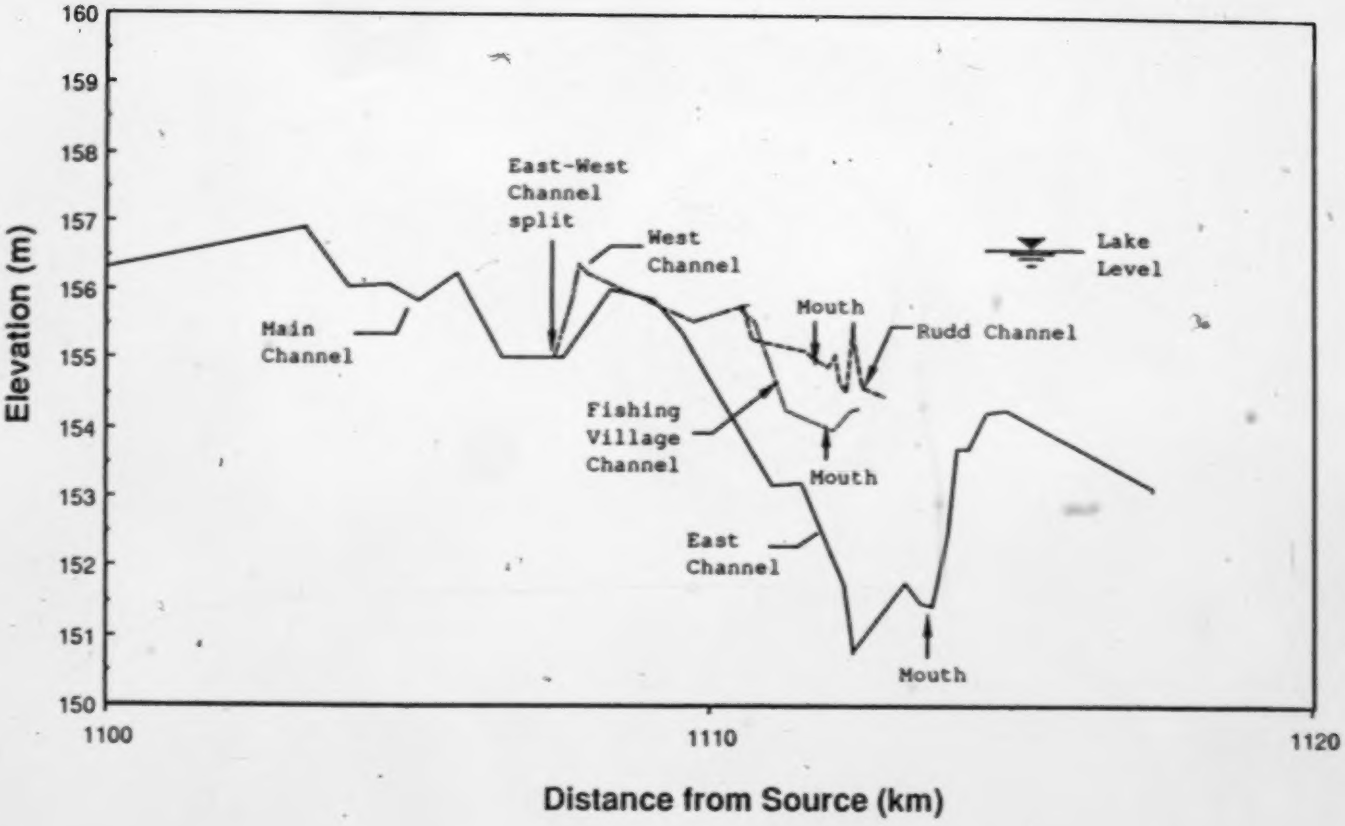


Figure 2.9 Thalweg profile of the delta channels of the Hay River

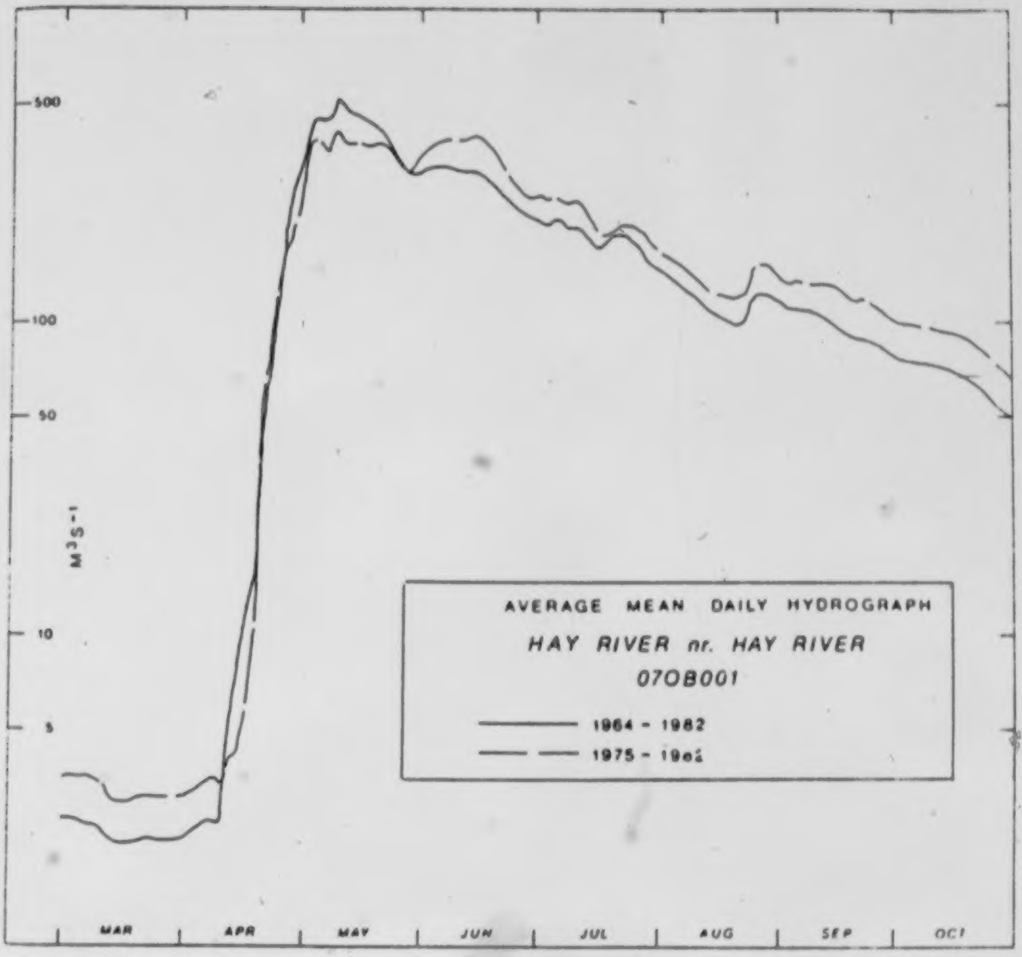


Figure 2.10 Average mean daily hydrograph Hay River near Hay River 07OB001 (modified from GNWT, 1984).

Table 2.1. Hydrometric stations in the Hay River Catchment

Water Survey of Canada Hydrometric Stations	Basin Area (square km)	Year it Began Operation
Hay River nr. Hay River	47900	63
Hay River at Border	46080	86
Hay River near Meander River	36900	74
Chinchaga River nr. High Level	10800	69
Steen River nr. Steen River	2610	74
Sousa Creek nr. High Level	818	70
Hutch Lake tributary near High Level	507	75
Lutose Creek nr. Steen River	292	80

2.4 Climate

The basin climate is classified as boreal. As such it is characterized by long, severely cold winters and short cool summers. The yearly average temperature for the region is 1.3 °C. Monthly averages of mean daily temperatures at the Town of Hay River fall below 0 °C in October, reach a minimum of -21 °C in January and return to zero in April, giving an average of 3150 °C of frost over the winter. The average accumulation of degree days of frost for Hay River and High Level are presented in Figure 2.11.

Average annual precipitation at Hay River is 340 mm and an approximate average for the total basin is 400 mm. The greatest precipitation occurs in the western regions of the basin. Figure 2.12 shows the average accumulation of total snowfall over the winter, for Hay River and High Level. The total for both Hay River and High Level is about 155 mm.

2.5 The Town of Hay River

The Town of Hay River is located in the delta of the Hay River. Continuous history in this community dates back to 1894 with the establishment of an Anglican mission. It is now a centre for northern marine transportation and for the

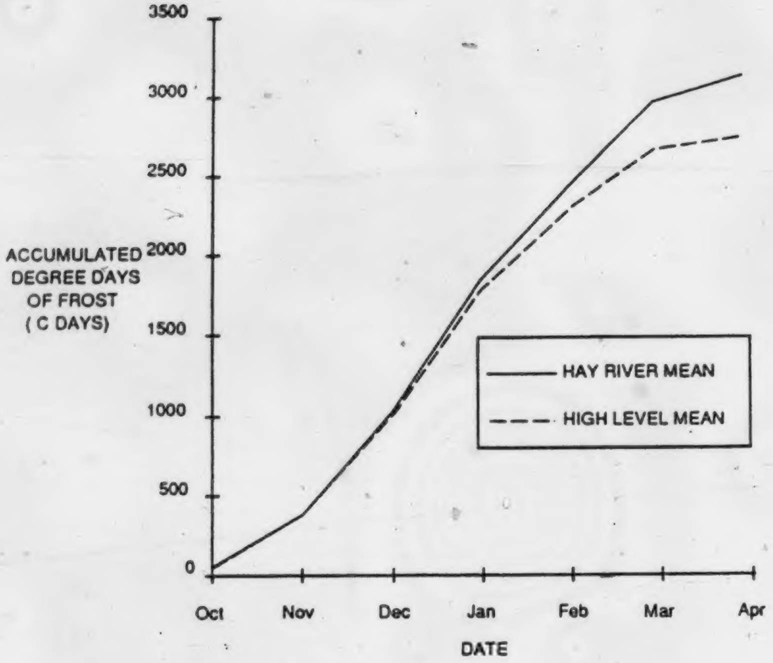


Figure 2.11 Average degree days of frost for the winter.

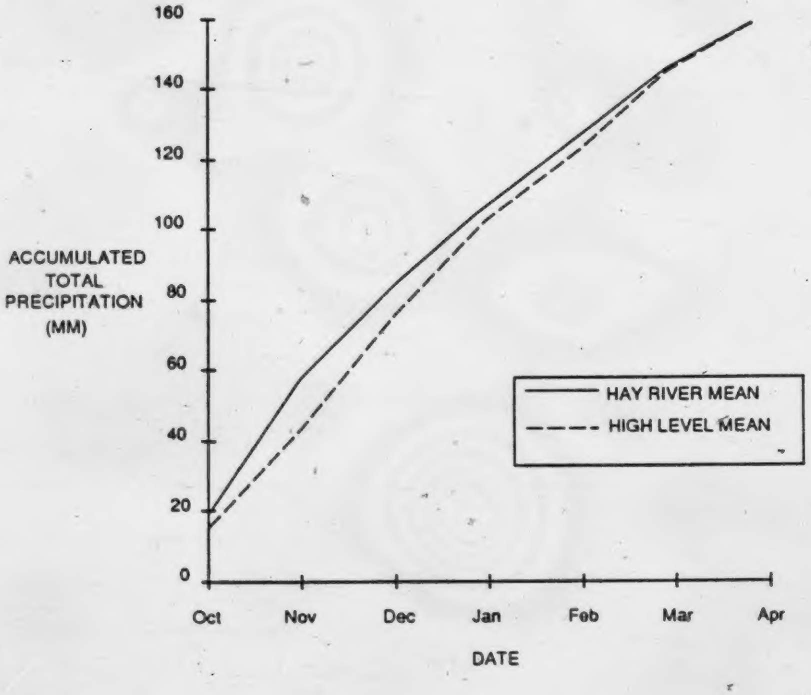


Figure 2.12 Average accumulted snowfall over the winter

commercial fishing industry on Great Slave Lake. Therefore its major role is as an inland port.

The Town of Hay River consists of four separate communities, as shown in Figure 2.7. The "Old Town" and "Fishing Village" are located on Vale Island. On the east bank of the East Channel is the original settlement, now known as the "Indian Village".

All three of the communities mentioned can suffer flooding during break-up. After severe flooding in 1963 the "New Town" was developed on the mainland, on the high west bank of the river about 6 km from the lake, an area free from flooding. The original intent was to relocate all activity in the New Town. Because of convenience much of the industry, and some of the residents, have remained on Vale Island, despite the establishment of the new townsite.

The marine industry in Hay River has made a number of changes to the river in the delta, including closing off a number of small channels to improve docking facilities.

2.6 Discussion

From the background information it was evident that one of the most significant features of Hay River, in terms of ice jams, was the complex morphology of the delta. The complex morphology makes the deterministic analysis of the site difficult. Therefore much information on the site was needed before any deterministic analysis could be done. This information was collected from past studies and reports on the area, field surveys of river and lake geometry, review of historical information, and documentation of the ice regime of the river.

3. Past studies

3.1 General

Three studies have been done on ice jam flooding in the Town of Hay River. Two of these studies were prepared by Stanley, Grimble, Roblin Ltd. (1959 and 1963) for the Department of Northern Affairs and Natural Resources. In 1979 Underwood McLellan (1977) Ltd. prepared a report to be used in developing flood risk lines for the Town of Hay River. A number of other small reports on break-up at Hay River from various Public Service Agencies have also been prepared.

3.2 Stanley, Grimble, Roblin Ltd. (1959)

This report was completed in 1959. Its purpose was to bring together all available reports, data, opinions and observations related to the flooding problem. With this information a number of solutions were proposed to eliminate or lessen the severity of ice jam floods. At the time of the study there was general lack of understanding of river ice hydraulics. As stated in the report: "It is difficult to calculate the effect of floating ice, but it is to be expected that the presence of ice, in proportion to water, would cause more rise than the water alone." Never-the-less the report provide a good source of data on ice jam flooding in Hay River.

The solutions proposed were very preliminary and it was recommended that a much more in depth analysis was needed before any of them should be implemented. The solutions presented could be broadly classed into four groups: altering the channel morphology in the delta; diking Vale Island; diversions or reservoirs far upstream to reduce peak flows; and modifying, weakening the ice in the spring. It is of interest that they estimated that diking Vale Island would cost approximately $160,000 in 1959. This figure is much less than the damage experienced as a result of ice jam flooding in 1963.

3.3 Stanley, Grimble, Roblin Ltd. (1963)

After severe flooding in 1963 another report was prepared that reiterated some of the possible solutions from the first report. It also presented flood levels that occurred in Hay River during the 1963 flood, from aerial photographs taken during the flood.

The two reports by Stanley, Grimble, Roblin Ltd. provided valuable historical information on flooding in the past. Included in both studies was an appendix which listed a number of government documents on flooding in Hay River from 1950 to 1963.

3.4 Underwood McLellan (1977) Ltd.(1979)

This report was prepared for the Department of Fisheries and the Environment. Its purpose was to develop the basis for flood zone delineation for the Town of Hay River. The study area extended from Great Slave Lake to a point approximately 30 km south of the Town of Hay River.

Flood levels along this reach were synthesized by estimating discharges for various return periods from a frequency analysis of the WSC gauge at Hay River. To convert the discharge to water levels along the reach, the HEC-2 model was used. The analysis was carried out for both open water and for a fully-developed ice jam at each cross-section along the river. For this analysis the hydraulic geometry of the river and the delta channels were needed. Some cross-sections were surveyed over the reach and further cross-sections were interpolated.

To provide some information on the break-up ice regime in the delta for the analysis, the spring break-up of 1977 was documented as part of the study. Unfortunately this break-up was one of the mildest on record. As stated in the report: " The extended break-up period and resulting ice jams were not representative of historic ice jams and were therefore not too useful in the actual analysis of the ice jam regime."

3.5 Public Agencies

Various Public Agency memos and reports were found on flooding in Hay River. Two of the larger sources of memos and documents were the Department of Highways and the Town of Hay River. Much of the Department of Highways information was for the period 1947 to 1963 when a fill was in place across the West Channel to provide access to Vale Island. This fill was washed-out almost yearly during spring break-up. In many years the Department of Highways monitored this fill during break-up and recorded the observations in memos.

The majority of the information from the Town of Hay River came from records of the Town Flood Watch. After severe flooding in 1963 the Town Flood Watch was set up. Its purpose was to monitor break-up to provide some warning of severe flooding. In most years a record was kept of the observations but the quality of these records seems somewhat dependent upon the time from the last significant flood. After a severe flood very detailed records were kept during the monitoring, but if no severe flooding took place in the years following the record quality degenerated.

Other sources of information were from government reports. Following the report from UMA (1979), Environment

Canada (1983) set flood risk levels (1 percent flood levels) for the Town of Hay River. Originally these flood levels were to be based upon the work carried out by UMA (1979). However the 1 percent flood level presented in that report was less than some of the events that had occurred in the past. Hence flood risk levels were set at the higher of either the historic level or the synthesized level from discharge estimates. It was found that in the area of Vale Island the historic levels were almost always higher than the synthesized levels. Hence along the East Channel the flood risk levels were set at the 1963 flood levels. Along the West Channel the levels were set at the 1974 flood levels. The flood risk map for the Town of Hay River was published with these levels in 1983.

In 1985 severe flooding occurred in the West Channel. In some locations the peak water levels were over one metre above the flood risk lines set in 1983. The Department of Indian and Northern Affairs contracted Underhill Engineering Ltd. (1985) to document the high water levels caused by this event in the Town area.

3.6 Other sources of information

Much information on flooding was obtained from residents of the Town of Hay River. Of special note is the information provided by long-time-resident 'Red' McBryan, a retired superintendent of Highways and former Mayor of Hay River. He has taken special interest in flooding at Hay River and has been the organizer of the Town Flood Watch for many years. Many of the aerial observations of break-up, undertaken as part of the present study, were guided by Red McBryan who shared his experience and identified physical features and described the normal series of events leading to break-up.

Another resident from whom much information was obtained is Dr. David Harrison, a teacher at Diamond Jenness High School in Hay River. His PhD dissertation on the history of Hay River (Harrison, 1984) provided much information on the early years of Hay River. He also provided a copy of a high school class project in which students had gathered detailed information on the history of ice jam flooding in Hay River.

Finally information was obtained on flooding from the local Hay River newspapers. The 'TAWPE', from 1961 to 1978, and the 'Hub' from 1977 to present.

3.7 Discussion

The review of the existing information on ice jam flooding in Hay River found that there was a general lack of quantitative data on the break-up process.

The quantitative data for this study was obtained from two methods. One method was to review available qualitative historical information and assign quantitative values to levels and locations described. The second involved documenting the ice regime in Hay River over the period of the study. This also involved documenting the hydraulic geometry of the delta. This is described in the next Chapter.

4. Field Data Collection

4.1 General

For the analysis of flooding in Hay River it was necessary to document the hydraulic geometry of the delta region. This was done during summer field work from July 6 to July 22, 1987. Included in this work was hydrographic surveys of the river reach and the lake near the mouth, tying temporary benchmarks into Geodetic Survey of Canada datum, and tying salient historical features into geodetic datum for use in the historical probability analysis described later.

4.2 Cross sections

Cross sections of the Hay River were surveyed over a reach extending from just upstream of the Water Survey of Canada gauge site to the mouths of both the West and East Channels, as shown in Figure 4.1. The cross section locations were chosen to give good representation of the channel geometry. A temporary bench mark was established at each cross section and tied into GSC datum. (Problems existed with some of the GSC bench marks because of the unstable soil in the area. On the basis of a 1983 report on the reliability of bench marks in the area by Underhill and

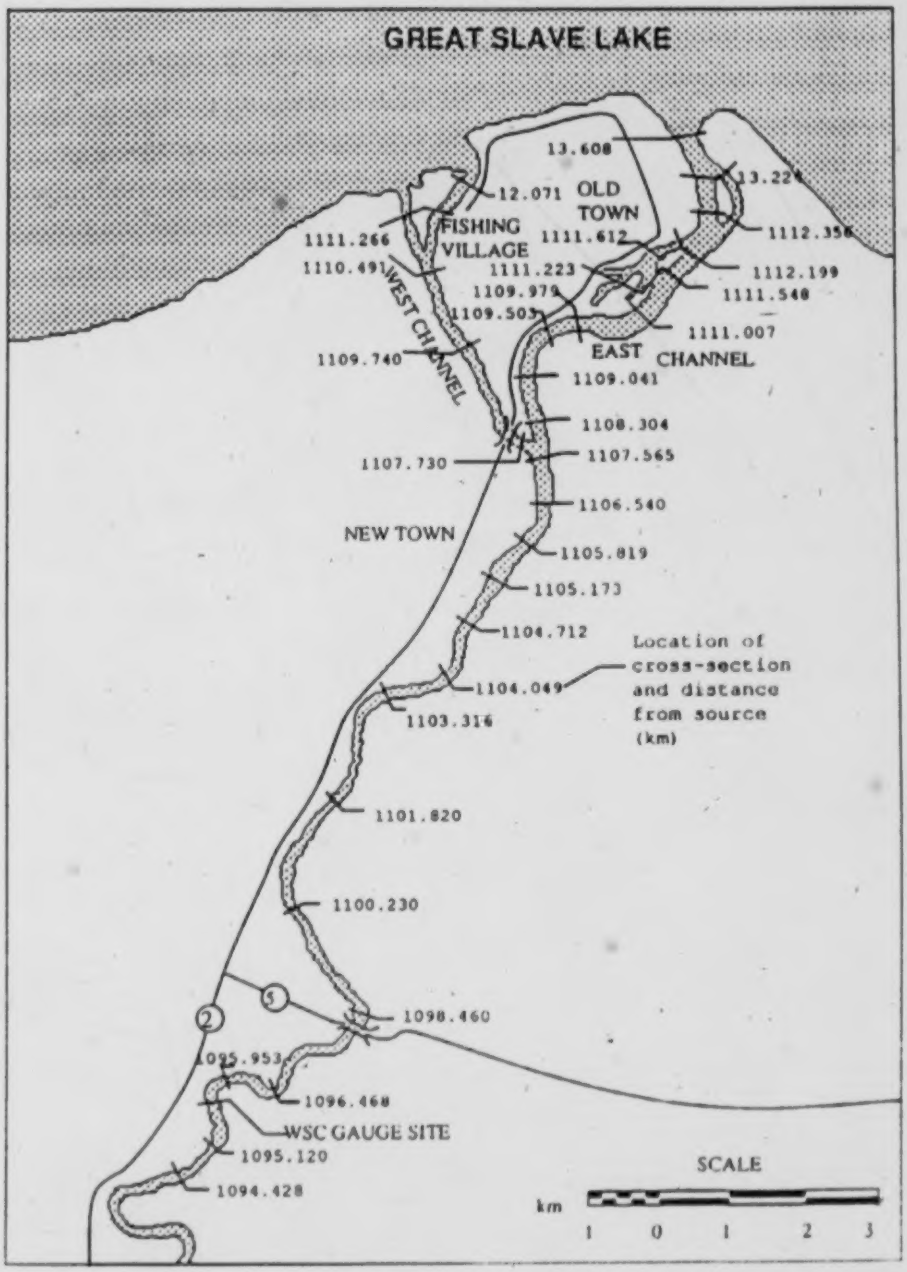

GREAT SLAVE LAKE
13.608
13.224
12.071
OLD TOWN
FISHING VILLAGE
1111.266
1110.491
WEST CHANNEL
1111.612
1111.223
1109.979
1109.503
1112.356
1112.199
1111.548
1111.007
EAST CHANNEL
1109.740
1109.041
1108.304
1107.730
1107.565
1106.540
NEW TOWN
1105.819
1105.173
1104.712
Location of cross-section and distance from source (km)
1104.049
1103.316
1101.820
1100.230
1098.460
5
2
1095.953
1096.468
WSC GAUGE SITE
1095.120
1094.428
SCALE
km
1 0 1 2 3

Figure 4.1 Location plan of cross-sections

Underhill (1983) and conversations with the staff, six G.S.C. benchmarks were selected for use. The benchmarks are listed on Appendix B.)

The cross sections were surveyed using a 14 foot Lund aluminum boat powered by a 35 HP Johnston outboard motor fitted with a jet leg to allow use in shallow water. Water depths were measured using a Ratheon DE-719B Fathometer, with the transducer mounted to the side of the boat, as shown in Figure 4.2 and 4.3. Distance across the channel was measured with a 'Topofil'. Bank profiles were surveyed using a standard rod and level technique. At each cross section an estimate of the bed material was made (where possible) and the type and height of vegetation on the banks was noted. The surveyed cross sections are presented in Appendix C. Typical cross sections of each of the East and West Channels and the Main Channel are shown in Figures 4.4, 4.5 and 4.6. A longitudinal profile of the thalweg was also sounded and used to develop the thalweg profile.

4.3 Lake bathymetry

To analyze flow from the river into the lake, information is needed on the lake bathymetry in the region of the outlets of the two channels. These areas were surveyed using the same echo sounding equipment used in the river survey. Perpendicular lines from shore were run with the

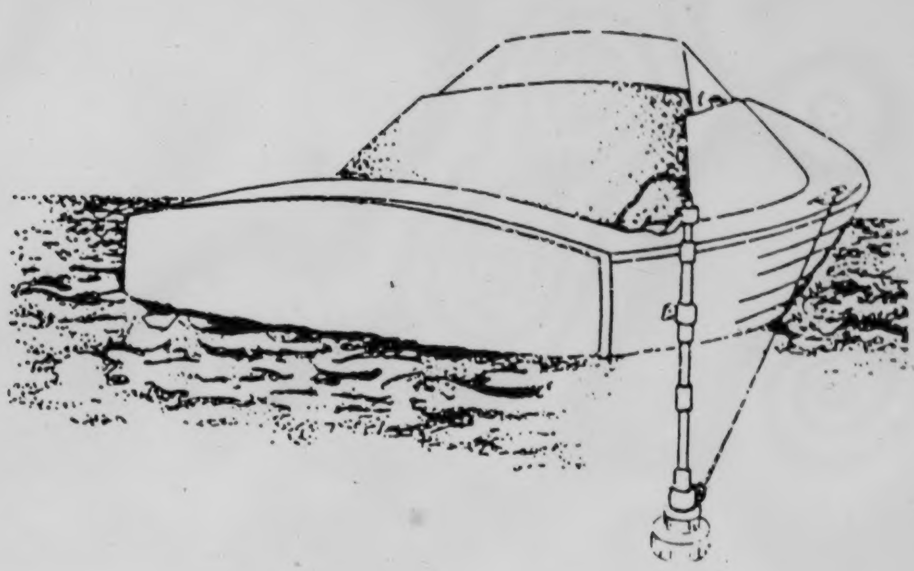


Figure 4.2 Typical transducer installation on boat.

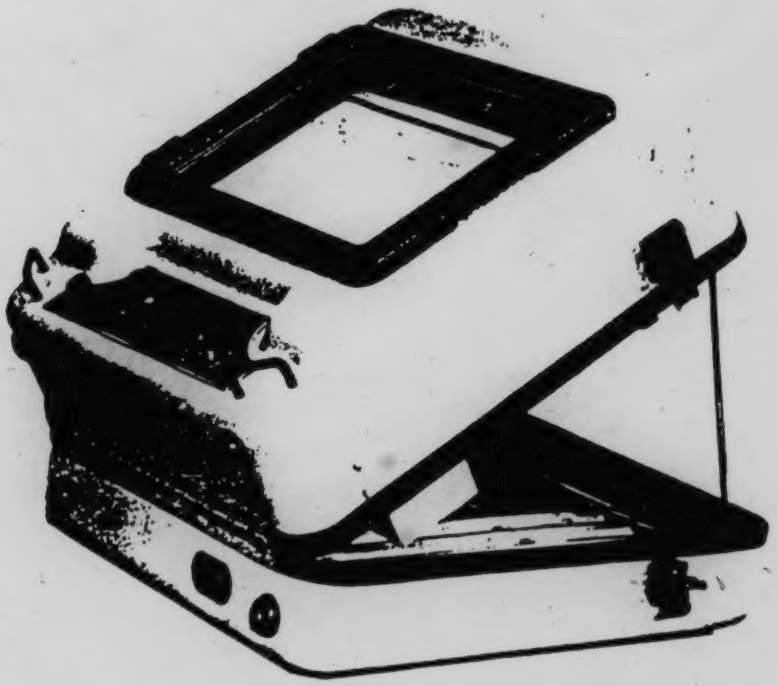
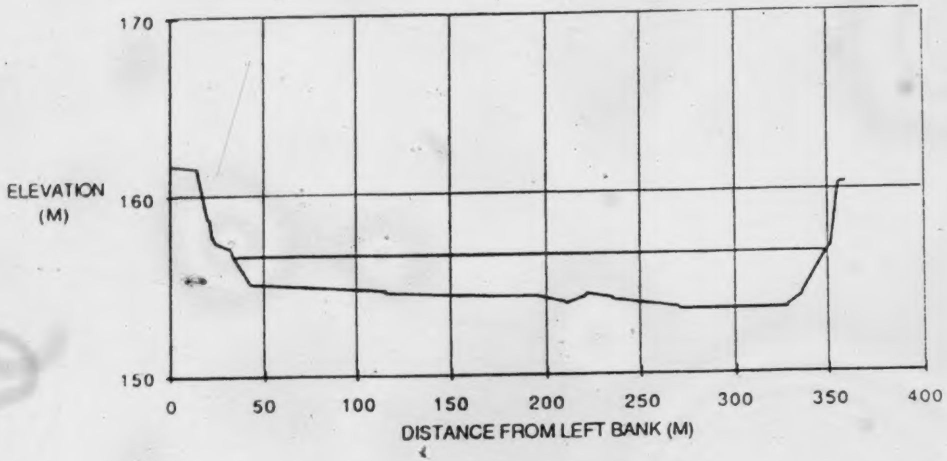


Figure 4.3 Recorder in operation position.



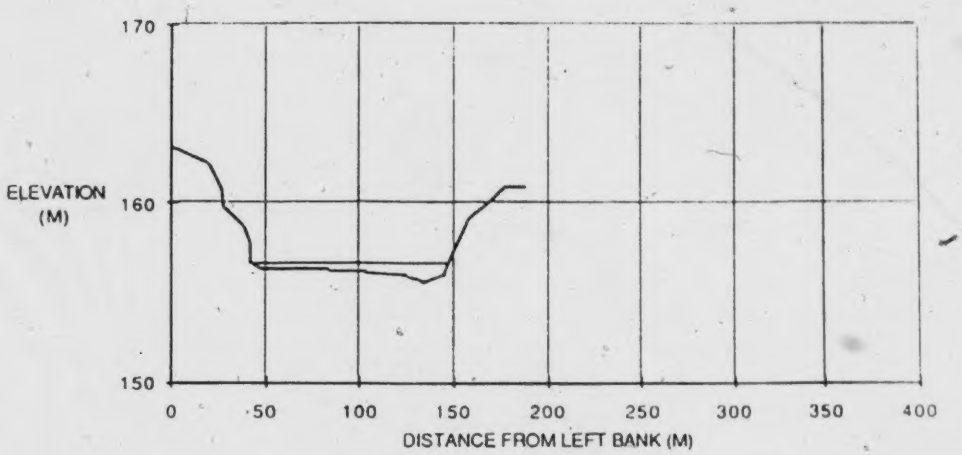
DISTANCE FROM LEFT BANK (M)	ELEVATION (M)
0	161.7
14	161.53
19.6	158.79
21.5	157.91
23.8	157.41
32.2	157.07
33.3	156.73
43	155.1
115	154.59
173	154.29
195	154.3
210	153.88
221	154.39
235	154.09
270	153.58
328	153.68
336	154.29
349	156.73
351	156.92
356	160.49
359	160.52

CROSS SECTION KM 1111.01 EAST CHANNEL

DESCRIPTION: This cross section is of the East Channel, about at the middle of Island C-D. The left bank is the grassy man made berm,, that surrounds Island C-D. A high cut bank is present on the right bank (355 m). The top of the cut bank is a grassed area which contains a number of houses. The bed material is gravel but a D_{50} was not determined. Water level of the day of survey, July 11, 1987, was 156.73 m.

TBM: Spike in tree on the left bank on the west side of the berm, at -5 m on the cross section. Elevation - 160.391 m.

Figure 4.4 Cross section km 1111.01 East Channel



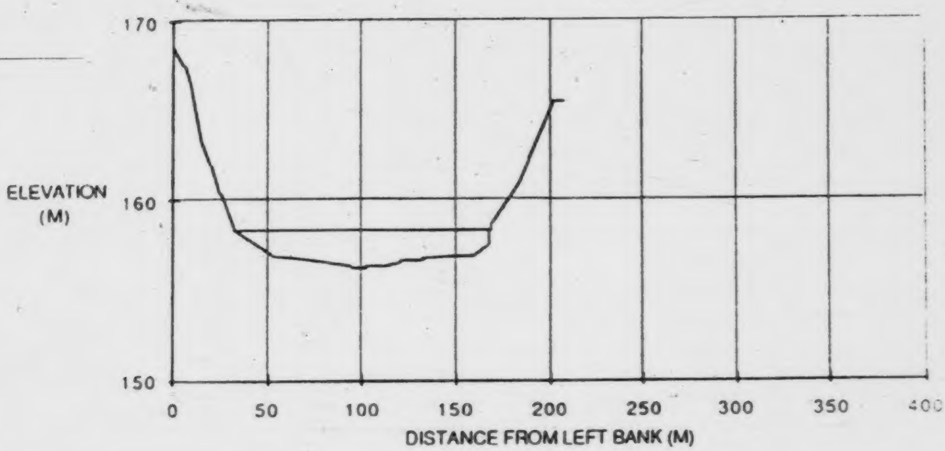
DISTANCE FROM LEFT BANK (M)	ELEVATION (M)
0	163.15
20	162.22
27	160.83
29	159.67
38	158.68
41.8	157.71
42	157.74
42.2	156.7
47.2	156.29
63	156.19
103	156.09
125	155.88
133	155.58
145	156.09
147.2	156.7
158	159.19
168	160.19
177	160.99
188	161.02

CROSS SECTION KM 1109.74 WEST CHANNEL

DESCRIPTION: This cross section is of the West Channel, 1.8 km D/S of the East - West Channel split. The left bank is treed from 0.0 m to 20 m, with grass from there to the water level. The right bank is grassed from the water level all the way up. No trees are present on this bank since the top is the airport runway. The bed material is gravel but the D50 was not determined. Water level on the day of survey, July 16, 1987, was 156.70 m.

TBM: Spike in tree on the top of the left bank at NE edge of the clearing, at 0.0 m on the cross section. Elevation - 163.745 m.

Figure 4.5 Cross section km 1109.74 West Channel



DISTANCE FROM LEFT BANK (M)	ELEVATION (M)
0	168.58
6	167.56
9.5	166.25
15	163.29
20	161.99
25	160.35
32.2	158.38
52.2	156.96
73	156.65
94	156.25
102	156.35
112	156.35
120	156.65
132	156.75
152	156.86
158	156.96
167	157.56
168	158.38
169	158.8
183	160.94
189	162.27
202	165.48
208	165.46

CROSS SECTION KM 1105.17

DESCRIPTION: This cross section is 2.7 km U/S of the East - West Channel split.The left bank is a steep slope with gravel and some grass present. The right bank is grassed with patches of gravel from the water level until 202 m at which point poplars begin. The bed material was estimated to have a D_{50} of 70 - 80 mm. Water level on the day of survey, July 9, 1987, was 158.38.

TBM: Hub in ground at 25 m on cross section. Elevation 160.440 m.

Figure 4.6 Cross section km 1105.17 Main Channel

boat being kept on line through use of a transit on shore and two-way radio communication. Distance from the shore was determined with the use of the "Topofil". The lines were run out to a depth of about 5 m. Generally this required a line over one kilometer long. Lines were also surveyed parallel to the shore, with the position of the boat again being tracked by transit.

The bathymetry of the area surveyed is shown in Figure 4.7. It can be seen that a bar was found to exist off shore, varying from about 750 m off shore directly in front of the West channel to less than 500 m adjacent to the East Channel.

4.4 Discussion

Documentation of the hydraulic geometry provided some of the basic data needed for the analysis of the ice jam flooding in Hay River. The first step in this analysis was to quantify the severity of flooding in Hay River. This was done by carrying out a probability analysis of flood levels in the delta region to palce the various historical events into context.

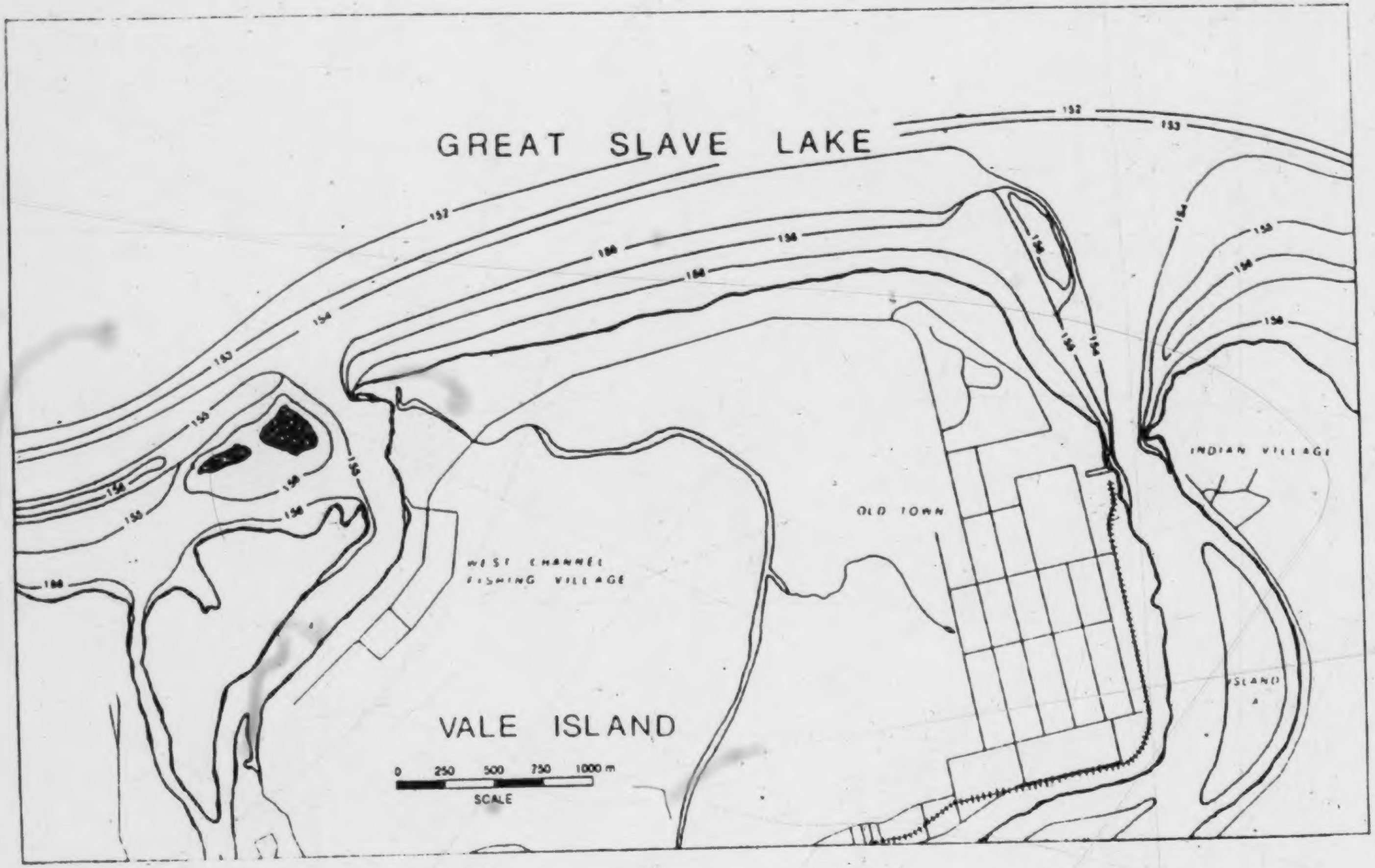

GREAT SLAVE LAKE
152
153
154
155
156
OLD TOWN
INDIAN VILLAGE
ISLAND A
WEST CHANNEL FISHING VILLAGE
VALE ISLAND
0 250 500 750 1000 m
SCALE

Figure 4.7 Lake Bathymetry

5. Probability Analysis

5.1 Introduction

Hydrological phenomena are normally analyzed by either deterministic or stochastic methods. Deterministic methods follow from physical laws. However in nature the causative factors influencing hydrological phenomena are so numerous that deterministic methods can not include them all in the analysis. Consequently purely deterministic methods should only be used under controlled artificial conditions. In nature the majority of hydrological phenomena are stochastic (or probabilistic) processes. On the other hand the use of only stochastic methods can lead to an analysis of data without a sound theoretical background. This can give results that are physically impossible. Yevjevich (1970) states:

> "The world's leading hydrologists maintain that a simultaneous use of both deterministic and stochastic (or statistical) methods of analysis and description of hydrologic processes in nature is necessary for producing the best scientific and practical information for hydrology"

Probabilistic analysis of flood data at a site can discover any regularities at the site and verify or aid in the formation of hypotheses for deterministic methods. It is therefore desirable to use probabilistic (or stochastic) methods to analyze flood data before the use of deterministic methods. For these reasons, and to quantify the severity of flooding in Hay River, a probability analysis was completed.

All high water levels in Hay River were associated with ice jams. Unlike open-water conditions where discharges, and thereby water levels, can be transposed from other locations, ice jams can be very site specific and very brief, making it difficult to transpose information to even nearby sites. It was therefore necessary to use information and methods seldom considered in more temperate areas.

Two approaches can be used to obtain ice jam flood level data: the direct analysis of historical data and/or the analysis of data synthesized from discharge estimates and ice jam mechanics. Synthesizing flood levels for ice jam conditions is much more difficult than for open-water conditions. For Hay River the complex morphology of the river delta and its influence on ice jam formation, and a lack of discharge estimates for many of the years, made synthesized levels unreliable. Consequently the analysis of historical data was preferred.

Historical data can come from many sources. These include the familiar hydrometric records, but also sources such as resident recollections , memoirs, archives, photographs, and environmental evidence. If available, all of the above sources must be utilized in data-poor areas, such as Hay River. However these sources generally have varying reliability, overlapping and broken periods of record and no well-defined reference levels.

5.2 Literature Review

When analyzing historical data from many sources there is some difficulty in tying the records together. A number of papers have been written on techniques to do this. The most familiar is Benson (1950) in which he used the Susquehanna River at Harrisburg, Pa., to illustrate his technique. Papers by Dalrymple (1960), Condie and Lee (1982) and Hirsch (1987) all expanded on Benson's method. Only a paper by Gerard and Karpuk (1979) used a different approach to the analysis of historical data.

Benson analyzed flood data at Harrisburg for the period 1786-1947. This data was comprised of historical data from one source for the period 1786-1873 and standard hydrometric records for the period 1874-1947. The historical data contained information on all floods above the 18 ft (5.6 m) stage, the height of the banks. In the analysis of this data, all flood peaks levels over 18 ft (5.6 m) were ranked and analyzed on the basis of a 162 year record (1786-1947). Then, for the period 1874-1947, for which standard hydrometric records were available, the flood peak levels below the 18 ft (5.6 m) were ranked and analyzed with a 72 year record. In doing this two years were ignored as high water was caused by ice jams rather than open water.

When these values were analyzed two distinct curves, with a discontinuity at the discharge corresponding to the 18 ft (5.6 m) stage, were formed. Benson believed that to obtain consistent results it was necessary to obtain an array of peaks properly representative of the single long period. To do this Benson weighted the flood peaks below the 18 ft (5.6 m) stage such that they represented the longer period. There were 57 years in the standard hydrometric record with stages below 18 ft (5.6 m). In the total record of 162 years there were 22 years with stages above 18 ft (5.6 m). Therefore there were 140 years with stages below 18 ft (5.6 m). He weighted the lower stages by assuming that each stage represented 140/57 or 2.456 years of record. He justified this in his statement: "The distribution of the flow during these 140 years is not known, but it can be assumed that the distribution is the same as is represented by the 57 years of known record which are below 18.0 ft." By using this technique the discontinuity was removed at the 18 ft (5.6 m) stage and a single curve could be fitted to the flood peaks.

This method was latter reiterated and formulated by Dalrymple (1960). He estimated the weighted rank for flood peaks below the base of the historical record as follows:

$$[5.1] \qquad m_1 = A + \frac{H-A}{T-A}(m-A)$$

m - order number where the highest is 1, the second highest 2, for all floods, both those for period of record and those from the historical data;

m_1 - order number of floods below base of historical record, adjusted to the time base of the total record;

A - the number of annual floods equalling or exceeding the lowest historical flood;

H - the length of the historical record in years, and

T - the total number of items, historical and recent, in the array

Using m_1 as the order number (or rank) and using the total record length, a probability estimate is obtained that weights the flood peaks below the base of the historical record.

Condie and Lee (1982) developed a maximum likelihood method for the analysis of historic data. They considered the historic floods as a censored sample, with the base of the historical record taken as the censor level. Although this method differs in approach from Benson's (1950) the result is much the same in that the flood peaks below the censor stage are weighted. Also the method only considers two sources of information, both with quantitative reference levels and continuous records.

The most recent paper on analysis of historical data is one by Hirsch (1987). This paper considers a number of plotting position formulae and analyzes any bias they may have in the analysis of historical data. Again in this paper all flood peaks below the censor level are weighted to remove any discontinuity in the distribution and only two sources are considered.

Gerard and Karpuk (1979) questioned the technique of weighting the flood peaks below the base of the historical record. In their paper they state weighting these flood peaks indeed removes the discontinuity at the censor stage, but there seems little justification for considering the upper group as absolute and forcing all the necessary adjustment into the lower group.

Gerard and Karpuk (1979) proposed an alternative, simple and systematic method to analysis historical data that can utilize many sources of data. This method introduces the concept of "perception stage" for each source of information, a concept similar to a censor stage. Perception stage is defined as the stage above which it is estimated the source would have provided information on the flood peak in any given year. The assessment of the perception stage for each source of information is generally a subjective exercise but, once allocated, it provides an objective means whereby data from various sources can be simply merged to estimate the probability distribution.

To obtain a probability estimate for a given flood peak a length of record and a rank must be assigned to it. Using the perception stage method the number of years of record associated with each peak is given by the sum of all the years with a perception stage at or below the level of that peak. A rank for the peak is determined by ranking all peaks in the group having a perception stage at or below the level of the peak of interest.

5.3 Analysis

The data for Hay River comes from multiple sources and therefore has more than one censor stage. This makes weighting the values as suggested by Benson and others difficult, if not impossible, even if justified. Hence the method proposed by Gerard and Karpuk (1979) was used in the analysis of Hay River as it is the only which allows consideration of more than two sources and does not involve weighting one section of the record in preference to another.

5.3.1 Sources of Data

Most of the information for the period 1893-1950 was obtained from the history of the Town of Hay River prepared by Harrison (1984), rather than from the original sources. The recorded history of Hay River began in 1868 with the establishment of a Hudson's Bay Company post. This post lasted 10 years but the only information available about the post dealt with the quantity of fur traded. In the fall of 1893, St. Peter's Anglican Mission and Residential School was established, followed by St. Anne's Catholic Mission in 1900. The dairies of these missions are the only records up to 1947. As both missions were located near the mouth on the east side of the East Channel, as shown in Figure 5.1, the information on flooding only pertained to that site.

Development started on Vale Island in 1939 after the discovery of gold in Yellowknife. An overland route from the south was needed to deliver supplies to Yellowknife. A winter road was completed from Grimshaw, Alberta, the northern terminus of the railroad, to Hay River. This road was called the Grimshaw Trail. With construction of the winter road activity in Hay River increased, but little in the way of new development took place.

The outbreak of World War II created an increased interest in Canada's north. The CANOL project was started with the entry of the United States into the war effort. Its purpose was to supply Alaska with fuel from Norman Wells. In

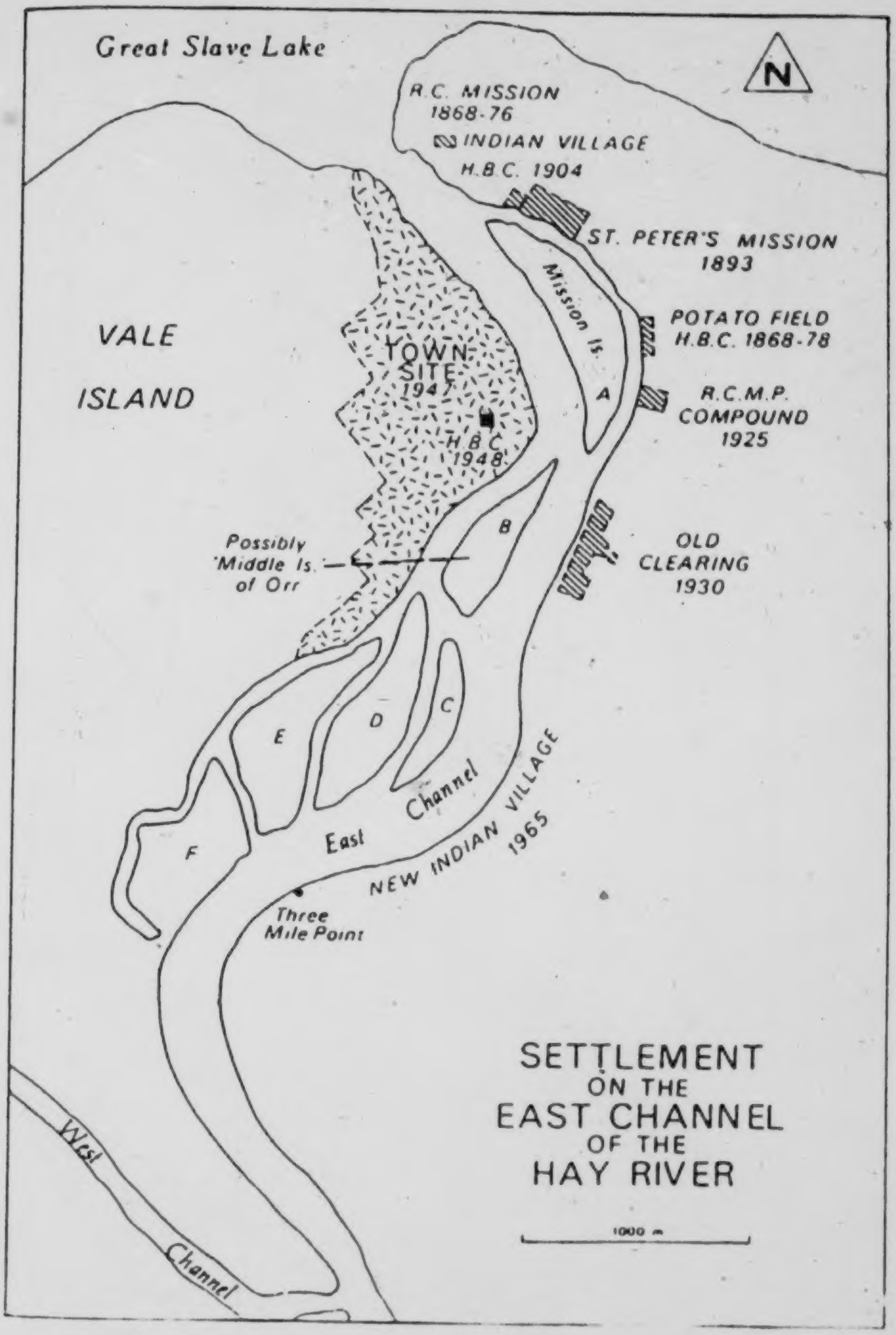

Great Slave Lake
N
R.C. MISSION
1868-76
INDIAN VILLAGE
H.B.C. 1904
ST. PETER'S MISSION
1893
Mission Is.
POTATO FIELD
H.B.C. 1868-78
R.C.M.P.
COMPOUND
1925
VALE
ISLAND
TOWN
SITE
1947
H.B.C.
1948
A
B
Possibly
'Middle Is.'
of Orr
OLD
CLEARING
1930
C
D
E
F
East Channel
NEW INDIAN VILLAGE
1965
Three
Mile Point
West Channel
SETTLEMENT
ON THE
EAST CHANNEL
OF THE
HAY RIVER
1000 m

Figure 5.1 Early Settlement on the East Channel (modified from Harrison, 1984)

1942 the United States Armed Forces started work on a transportation network to move men and supplies to the north. This included upgrading the Grimshaw Trail and construction of an air strip on the south end of Vale Island.

It was not until 1947, when an all-weather road was finally completed to Hay River, that major development was triggered on Vale Island. As the terminus of the road was to be the northeast corner of the Island, four earth fills were constructed across channels of the river, the most significant being the one across the West Channel.

The completion of the road also greatly increased the market for commercial fishing on Great Slave Lake. This was largely based at the mouth of the West Channel so this area became known as the Fishing Village.

With the development following completion of the highway much better records were kept by government departments, newspapers, and by the Town on flooding in the area. As a result of the severe flooding in 1963 a Town Flood Watch was established. Its purpose was to monitor the river and warn residents of any potential flooding. For many of the years since then records of the observations taken during the Watch are available. These records were a major source of flood data.

The information obtained from the above sources was mostly descriptive in nature and water level elevations had to be assigned on the basis of the description. For example, the following account of the flood of 1914 is contained in the records of the Anglican Mission: "May 1, 1914: It came into the Mission house, the floors of the dining room, kitchen and girls playroom were flooded halfway across... Water reached the stable and then receded." To estimate an elevation for the high water level it was first necessary to find the location of the places mentioned in the description. This was determined from the history of Hay River compiled by Harrison (1984). The levels of the salient features described were tied into geodetic datum during the survey work carried out in the summer of 1987 or were obtained from 1:2000 topographic maps.

5.3.2 Reconstructing the record

The separate communities located on different river channels, the complex geomorphic characteristics of the Hay River delta, and the local nature of ice jams, dictated that a number of prabability-stage relationships had to be developed to properly define flood levels for the Town of Hay River. As a compromise between available data and detailed definition of the levels, three sites were selected, one each near the mouths of the East and West Channels, and one at the split between the channels, as shown in Figure 5.2.

The nature of available record for each of the three sites is described below. The basis for the selected perception stage or level for each source for each year of

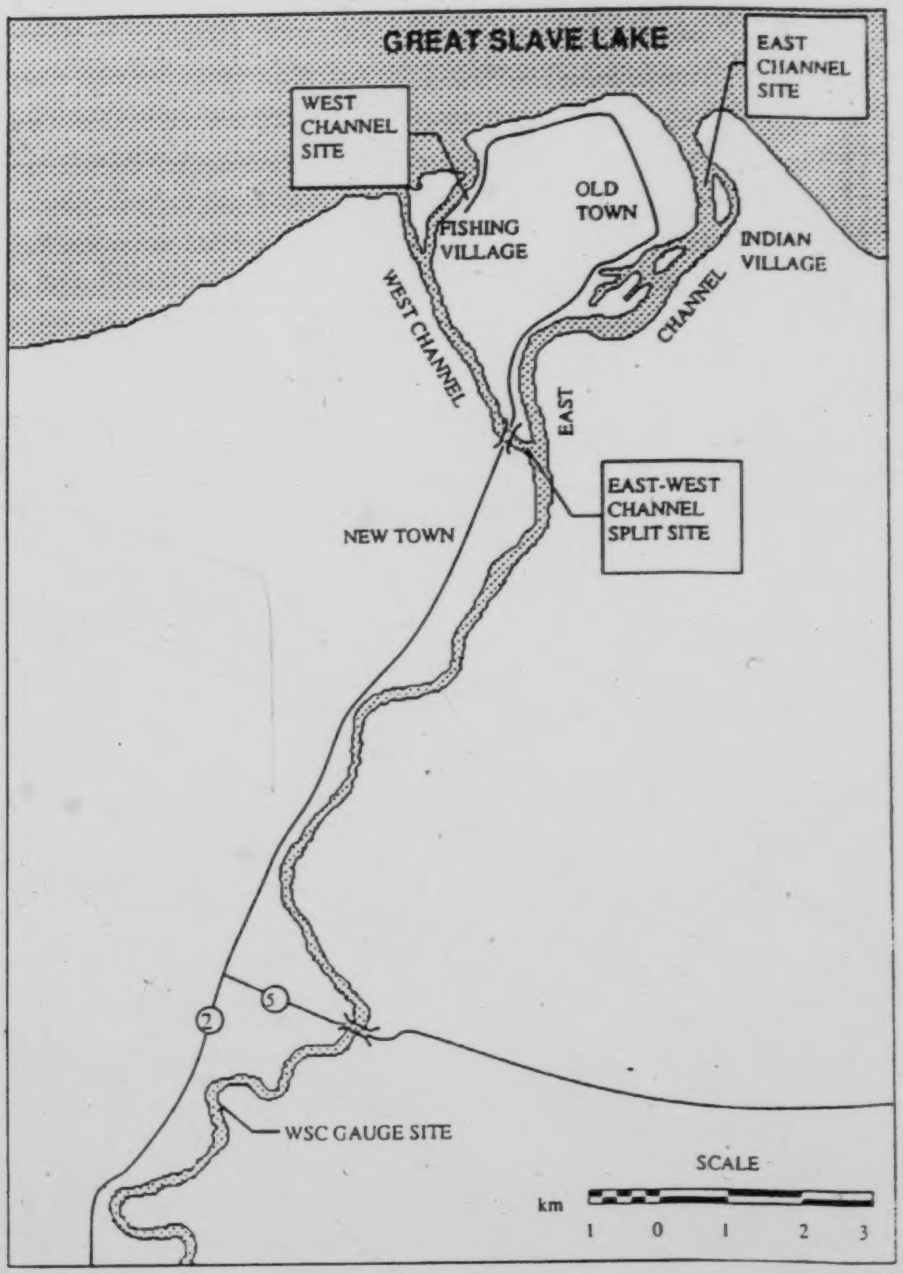

GREAT SLAVE LAKE
EAST CHANNEL SITE
WEST CHANNEL SITE
OLD TOWN
FISHING VILLAGE
INDIAN VILLAGE
WEST CHANNEL
EAST CHANNEL
EAST-WEST CHANNEL SPLIT SITE
NEW TOWN
2
5
WSC GAUGE SITE
SCALE
km
1 0 1 2 3

Figure 5.2 Location plan of probability analysis sites

'record' is also given. Appendix D contains a brief description of each available flood description as well as the basis for the peak water level estimate.

5.3.2.1 Site 1: Near the East Channel mouth

This site has the longest record of the three. Sources for the flood peak levels at this site can be broken into two broad categories. From 1894 to 1948 almost all the information was obtained (through Harrison (1984))from the diaries of the Anglican or Catholic Mission. Both were located on the east side of the East Channel. For this period the perception level was chosen as the top of the bank at the mission site, a geodetic elevation of 158.4 m.

The settlement of Vale Island began in 1948 and replaced the missions as the community centre . Flood levels after 1948 could then be obtained from Town flood-watch reports, newspapers, and government records. As the development on Vale Island was directly across the river from the Missions, these records were for the same location on the river as the Missions.

For the period 1948 to 1968 the perception stage was also taken as 158.4 m, as this is the elevation of the road which borders the river on the west bank of the East Channel. After 1968 the perception level was lowered to 158.1 as more development occurred between the road and the river.

However in 1956, 77, and 87, the peak flood levels were actually measured as part of studies triggered by considerations independent of flooding. Hence a zero preception stage was assigned to these years. Zero stage is equal to lowest possible stage, the bed level at the split and the lake level at the mouths. In 1979 a mention of the peak level was found in the town flood watch records. As this seemed independent of the level reached, a zero perception stage was also assigned to it.

These perception levels and the estimated flood peak levels for this site are summarized in Figure 5.3.

5.3.2.1 Site 2: East - West Channel split

Records of flooding at this site do not start until 1947 because there was no development at the site prior to this. As mentioned earlier, in 1946 construction started on an all-weather road from the south. As the terminus of this road was to be Vale Island, a fill was constructed across the West Channel to reach the island. The location of the fill was 100 m downstream of the East-West Channel split. As this fill was frequently over-topped during break-up, the Department of Highways monitored water levels routinely. This provided flood peak levels for many of the years up to 1963, when the fill was removed and replaced with a bridge.

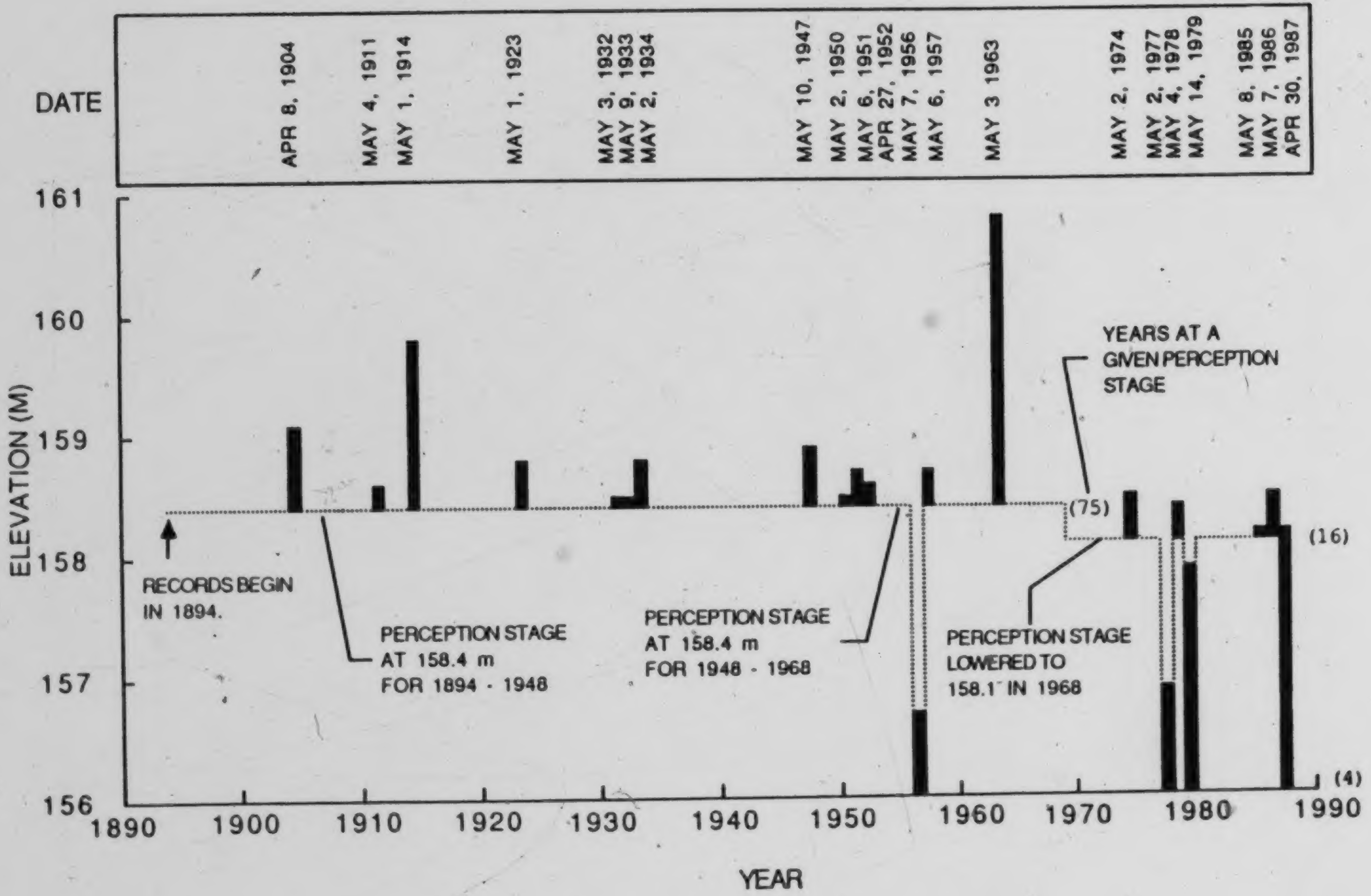


Figure 5.3 Water levels and percpetion stages for the East Channel near the mouth

The fill was partially completed in 1947 to an elevation of 158.0 m and finished to elevation 163.9 m in 1948. It was lowered to 161.0 m in 1953 because of concerns about its role in causing the flooding in 1951. It was totally removed in 1963 following completion of the West Channel bridge. A summary of the fill elevations is given in Figure 5.4.

In the spring of 1947 the fill was only partially complete and had an estimated elevation of 158.0 m. This was therefore chosen as the perception level for that year. For 1948-49 it is only known that the water did not flow over the fill and the perception level is therefore the elevation of the fill, 163.9 m. From 1950 to 1954 detailed reports were made on water levels during break-up by the Department of Highways. As these measurements were more a matter of routine than a direct response to high water levels a perception stage of zero was allocated to these years. After 1954, water levels were only reported if the fill was washed out, so the perception stage was chosen as 161.0 m, the height of the fill.

After 1963, when the fill was removed, the Department of Highways no longer monitored water levels, but they were monitored as part of the Town flood-watch. Although reports were available from the flood-watch, many of the records are missing and in some of the years the records are so vague that the peak level cannot be deduced. As the recording of break-up records are a routine exercise by the Town because of the annual flood threat, a zero perception

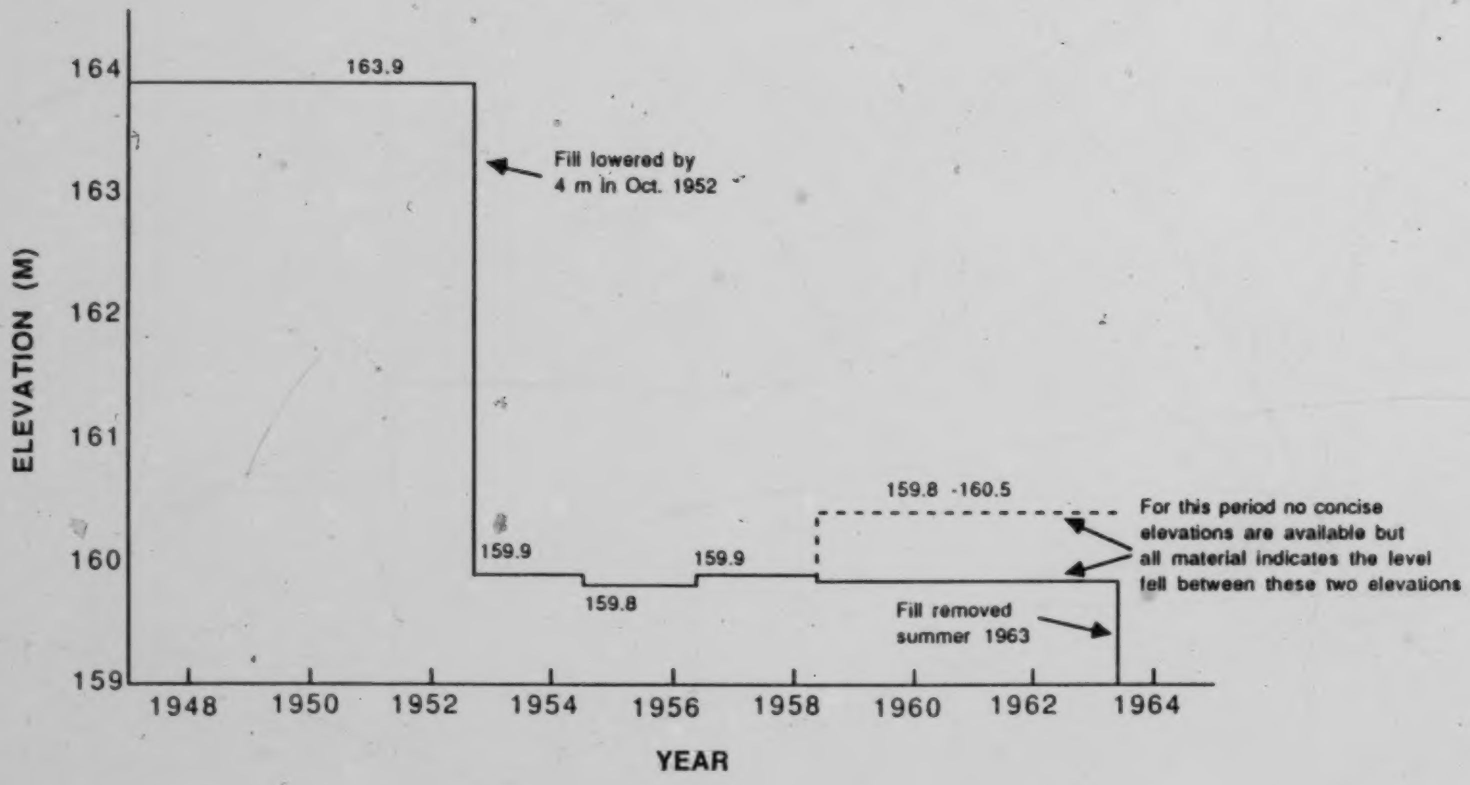


Figure 5.4 Variation in elevations of the fill across the West Channel

stage was allocated for the years where flood peak levels could be estimated from the town's records.

The perception stage for the years where records were not available, or peak levels could not be estimated, was more difficult to define. The river banks at this site are very high, as the highest ground in the whole area is located there. Using the top of the bank as the perception stage would be unrealistic, as the whole island would be underwater if water reached this level. It is also known that if major flooding takes place on the island, high water levels are documented by some government agency, or reports of flooding would appear in the newspaper. Therefore the perception stage was selected at a level at which flooding would occur downstream. Analysis of the historical records indicated that any water levels over 163.0 m at the split causes some flooding in the downstream reaches. This elevation was therefore chosen as the perception stage for the years where water levels could not be estimated from the break-up records, for the period 1964 to present.

The flood peak levels and perception stages for this location are given in Table 5.1 and summarized in Figure 5.5.

5.3.2.3 Site 3: Near the West Channel mouth

Although settlement of this area began in 1948, records of flooding do not start until 1964, as no flooding occurred

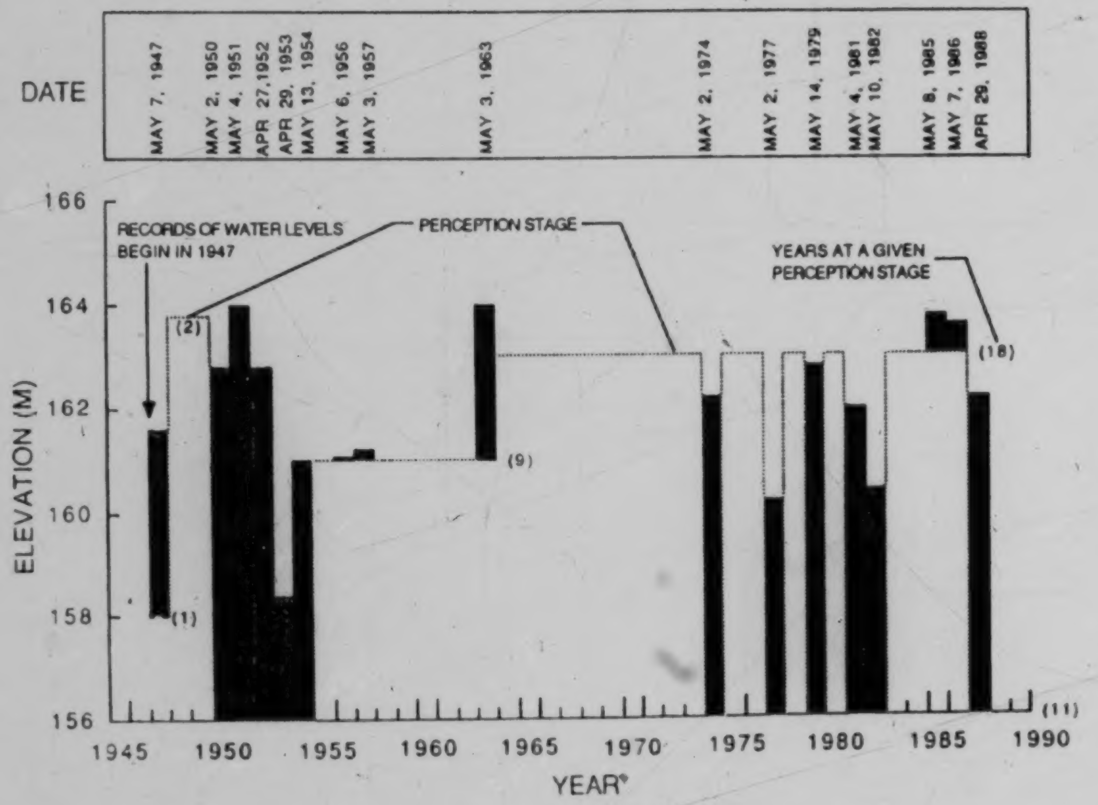


Figure 3.5 Water levels and perception stages for the East-West Channel Split

while a fill was in place across the West Channel. The major sources of data were Town Flood watch records or local newspapers. The perception stage was chosen as 158.5 m, the top of the bank in the West Channel Fishing Village. The flood peak levels and perception stages are given in Table 5.1 and summarized in Figure 5.6. As before, the years 1977 and 1987 were assigned zero perception stages.

5.3.3 Rank and record length

To obtain an estimate of the exceedence probability of a given level a rank and record length must be assigned to each event. As suggested by Gerard and Karpuk (1979) the summary diagrams, Figures 5.3, 5.5 and 5.6, allow a rank and record length to be allocated to each peak. The number of years of record associated with each peak is given by the sum of all the years with a perception stage at or below the level of that peak. A rank for the peak is determined by ranking all peaks in the group having a perception stage at or below the level of the peak of interest. For example, the peak level for 1987 near the mouth of the East Channel was 158.2 m. This elevation is lower than the perception stage for the Mission records (1894-1947) and for 1948-1968 so these periods cannot be included in the record length. However, this peak level is greater than the perception stage for 1956 and for the period 1968-87, so these years included in the

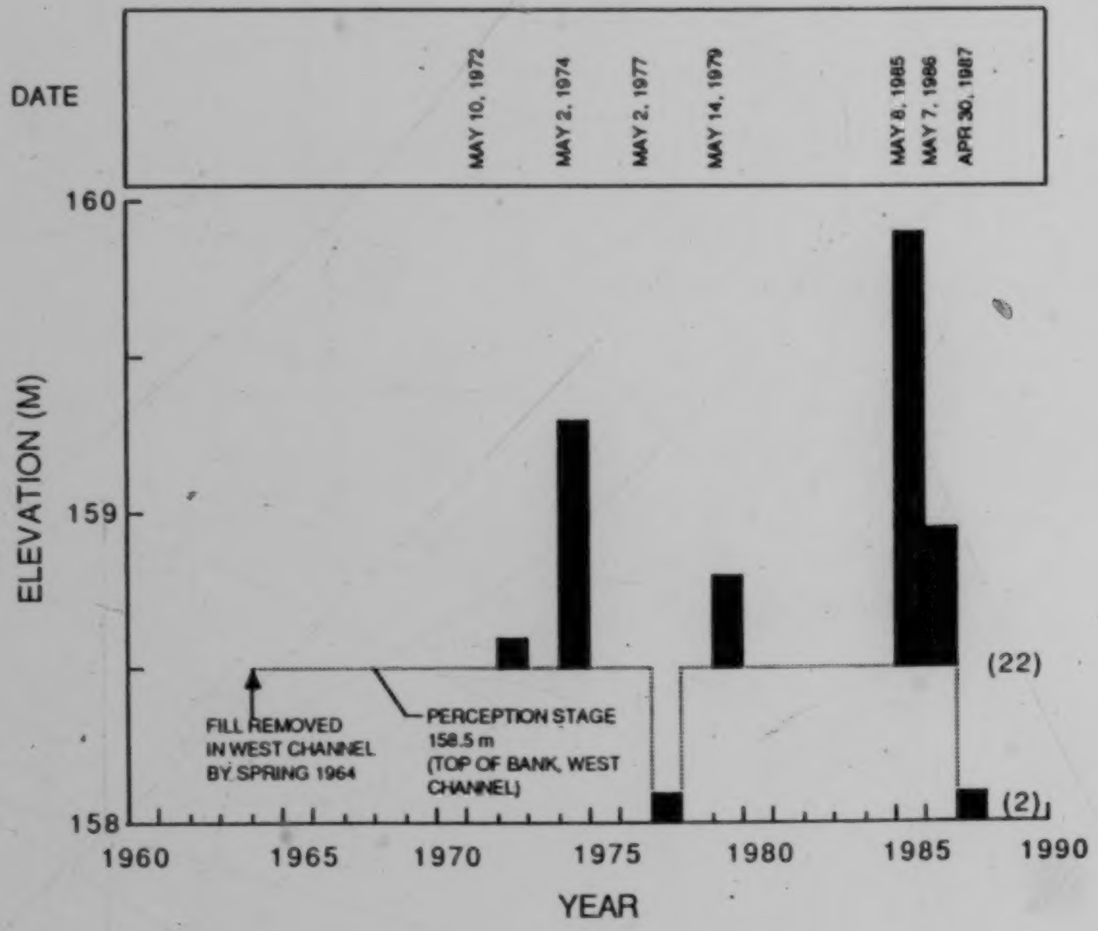


Figure 5.6 Water levels and perception stages for the West Channel near the mouth

record length. This gives a record length of 20 years to be allocated to the peak of 1987.

To obtain the rank of the 1987 peak, the peak must be compared to the other peaks with a perception stage lower than 158.2 m. Within this constraint the peak level of 158.2 m has been exceeded on four occasions- in 1974, 78, 85, 86 (note the peaks prior to 1968 are not included). Therefore the 1987 peak level has rank 5.

This process can be repeated for the other peaks. Table 5.1 summarizes the resulting ranks and record lengths for each event.

5.3.4 Reference stage and probability distribution

Because of the physical constraints on water levels produced by ice jams it is unlikely any of the standard probability distributions used in hydrology would have much to contribute to the better definition of the water level probability distribution. It was therefore felt sufficient to present the probability estimates graphically. The simplest distribution that can be expected to at least represent the lower portion of the distribution adequately is the log normal distribution, with zero-stage being taken as the minimum water level elevation at each site: ie. the zero-discharge stage at the East-West Channel split and the lake level at the two channels mouths. Because of the expectation

Table 5.1 Calculation of cumulative probabilities for break-up stages.

YEAR	HIGH WATER ELEVATION (M)	STAGE ABOVE ZERO-FLOW STAGE (M)	YEARS OF RECORD	RANK	PROBABILITY OF BEING GREATER THAN OR EQUAL TO (%)	95 PERCENT CONFIDENCE LIMITS (%)	
						LOWER LIMIT	UPPER LIMIT
EAST CHANNEL NEAR THE MOUTH							
1963	160.8	4.2	93	1	0.67	0.00	2.33
1914	159.8	3.2	93	2	1.74	0.00	4.40
1904	159.1	2.5	93	3	2.82	0.00	6.18
1947	158.9	2.3	93	4	3.89	0.00	7.82
1922	158.8	2.2	93	5	4.96	0.55	9.37
1934	158.8	2.2	93	6	6.03	1.19	10.87
1951	158.7	2.1	93	7	7.10	1.88	12.33
1957	158.7	2.1	93	8	8.18	2.61	13.75
1911	158.6	2.0	93	9	9.25	3.36	15.14
1952	158.6	2.0	93	10	10.32	4.14	16.51
1974	158.6	2.0	93	11	11.39	4.94	17.85
1932	158.5	1.9	93	12	12.47	5.75	19.18
1933	158.5	1.9	93	13	13.54	6.59	20.49
1950	158.5	1.9	93	14	14.61	7.43	21.79
1986	158.5	1.9	93	15	15.68	8.29	23.07
1985	158.5	1.9	93	16	16.76	9.17	24.35
1978	158.4	1.8	93	17	17.83	10.06	25.61
1987	158.2	1.6	20	5	22.84	8.70	49.00
1979	157.9	1.3	4	2	38.24	6.80	93.00
1977	156.9	0.3	3	2	50.00	1.30	98.70
1956	156.8	0.2	3	3	80.77	9.40	99.00
EAST WEST CHANNEL SPLIT							
1951	164.0	7.3	41	1	1.52	0.00	5.25
1963	164.0	7.3	41	2	3.94	0.00	9.89
1985	163.5	6.8	41	3	6.36	0.00	13.84
1986	163.4	6.7	41	4	8.79	0.12	17.45
1952	162.8	6.1	21	3	12.35	0.00	26.43
1979	162.7	6.0	21	4	17.06	0.97	33.15
1950	162.7	6.0	21	5	21.76	4.12	39.41
1974	162.2	5.5	21	6	26.47	7.60	45.34
1987	162.2	5.5	21	7	31.18	11.36	50.99
1981	161.9	5.2	21	8	35.88	15.37	56.40
1954	161.9	5.2	21	9	40.59	19.59	61.59
1947	161.6	4.9	21	10	45.29	24.00	66.58
1977	161.1	4.4	21	11	50.00	28.61	71.39
1957	161.1	4.4	21	12	54.71	33.42	76.00
1956	161.0	4.3	21	13	59.41	38.41	80.41
1982	160.4	3.7	12	11	86.73	57.00	98.20
1953	158.2	1.5	12	12	94.90	64.00	99.80
WEST CHANNEL NEAR THE MOUTH							
1985	158.8	3.3	24	1	2.58	0.00	8.92
1974	159.3	3.8	24	2	6.70	0.00	16.70
1986	159.0	3.5	24	3	10.82	0.00	23.26
1979	158.5	3.0	24	4	14.95	0.69	29.21
1972	158.5	3.0	24	5	19.07	3.35	34.79
1977	158.1	2.6	2	1	27.78	0.80	90.60
1987	158.1	2.6	2	2	72.22	1.30	98.00

of an approximate log normal distribution the probability estimates were based on the Blom formula, Pr= (m-3/8)/(N+1/4) where Pr is the estimated probability of the peak break-up stage being equal to or greater in any year than a given stage, m the rank and N the record length. The Blom formula provides an unbiased estimate of this probability for a log-normal distribution.

The results are presented in Figure 5.7. Evidently the log normal distribution does provide a reasonable description of the data.

A physical upper limit on flood stages should be considered for any probability analysis of ice jam flood levels. This level is particularly important if the distribution is to be used to estimate extreme events at a site. At a site with wide flood plains, water levels caused by an ice jam can only rise a little above the banks before the water is free to flow around the confined ice accumulation in the river. Calkins (1983) found that ice jam thickness data suggests that once bankfull depth is reached further thickening of the cover is minimal because the flow is now diverted into the floodplain. The lack of increase in accumulation thickness further suggests that water levels do not increase greatly once the water level is above bank level. This would be the case in Hay River as the delta region is extremely flat. The physical upper limits chosen for Hay River were therefore levels above which significant overbank flow around the ice jam could be expected. As

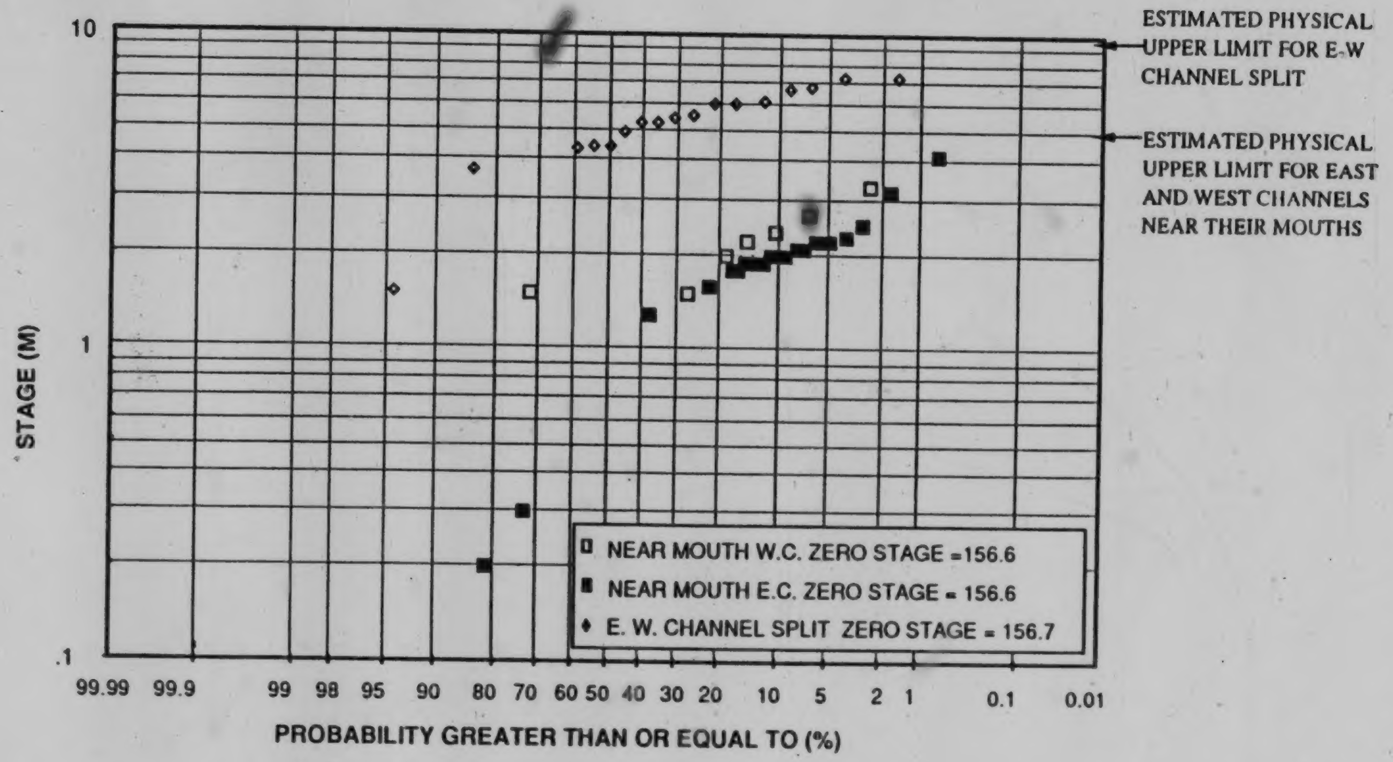


Figure 5.7 Cumulative probability of break-up flood levels

indicated in Figure 5.7, the water levels to date have been below the likely physical upper limit on stages at each site.

Confidence limits were calculated for each of the three distributions to provide an indication of the weight to attached to each point when deciding on a compromise distribution for each site. The method of calculating the confidence limits differed from the standard approach currently used in hydrology. In the standard method, confidence limits are calculated from the variance of the hydrological parameter of concern (for example, annual maximum discharge) and the years of record.

In the deriving the formula to calculate confidence limits the following relation (Hald, 1952) is used:

[5.2] $$\mathcal{V}\{u_H\} \approx \mathcal{V}\{P\}\left(\frac{du}{dP}\right)^2$$

where $\mathcal{V}\{\ \}$ is the variance, u_H is in this case the hydrological parameter and P is the exceedence probability . The value of du/dP is determined from:

[5.3] $$\frac{dP}{du} = \varphi(u)$$

where $\varphi(u)$ is the standard normal distribution function. From [5.2] and [5.3] it is possible to calculate the variance and thereby the confidence limits, for the hydrological data. However, the variable being estimated is the exceedence probability. It would therefore seem more appropriate, to present confidence limits for this parameter directly rather than to transpose them into estimates of confidence limits on the hydrological parameter using Equation 5.2. This is particularly so in the case of water levels where the use of the above technique will often lead to quite impossible upper limit water levels.

If the exceedence probability is assumed to be approximately normally distributed, the variance $\upsilon(P)$ is given by (Hald, 1952):

$$[5.4] \qquad \upsilon(P)=\frac{P(1-P)}{N}$$

The 95% confidence interval is given by:

$$[5.5] \qquad 1.96\sqrt{\upsilon(P))}$$

Some problems were encountered when the confidence intervals were calculated for the low stages at each site. Typically these levels are below the general perception stage and therefore are only associated with 3 to 5 years of record. With such small years of record it is unrealistic to assume the exceedence probability estimates would be normally distributed. For small values of N the confidence limits were calculated on the assumption that the exceedence probability estimates would follow a binomial distribution.

(that is there is an even chance of the estimated probability being above or below the true probability. As the number of samples increase the binomial distribution tends to the normal distribution). For a binomial distribution the 95% confidence limits are given by Hald (1952).

These confidence limits so calculated are presented in Table 5.1 and plotted in Figures 5.8 - 5.10. Some of the confidence limits for the lower data extend into the low probabilities even though they were associated with very low stages. This is merely indicative of the variability inherent in only a few years of record.

5.4 Discussion of probability analysis

As is evident from Figure 5.7, the analysis of the historical data provides a reasonably well-defined probability distribution for each site. An item of note is the similarity of the variance at each site. This is likely due to the fact that the discharge is an influential common denominator at each site.

Another item of interest is the apparent lack of influence of the several man-made changes to the morphology of the delta. It is commonly held by the residents of Hay River that flood levels have been higher and more frequent since various subchannels of the East Channel were cut-off for dock construction, beginning in 1947. However this is

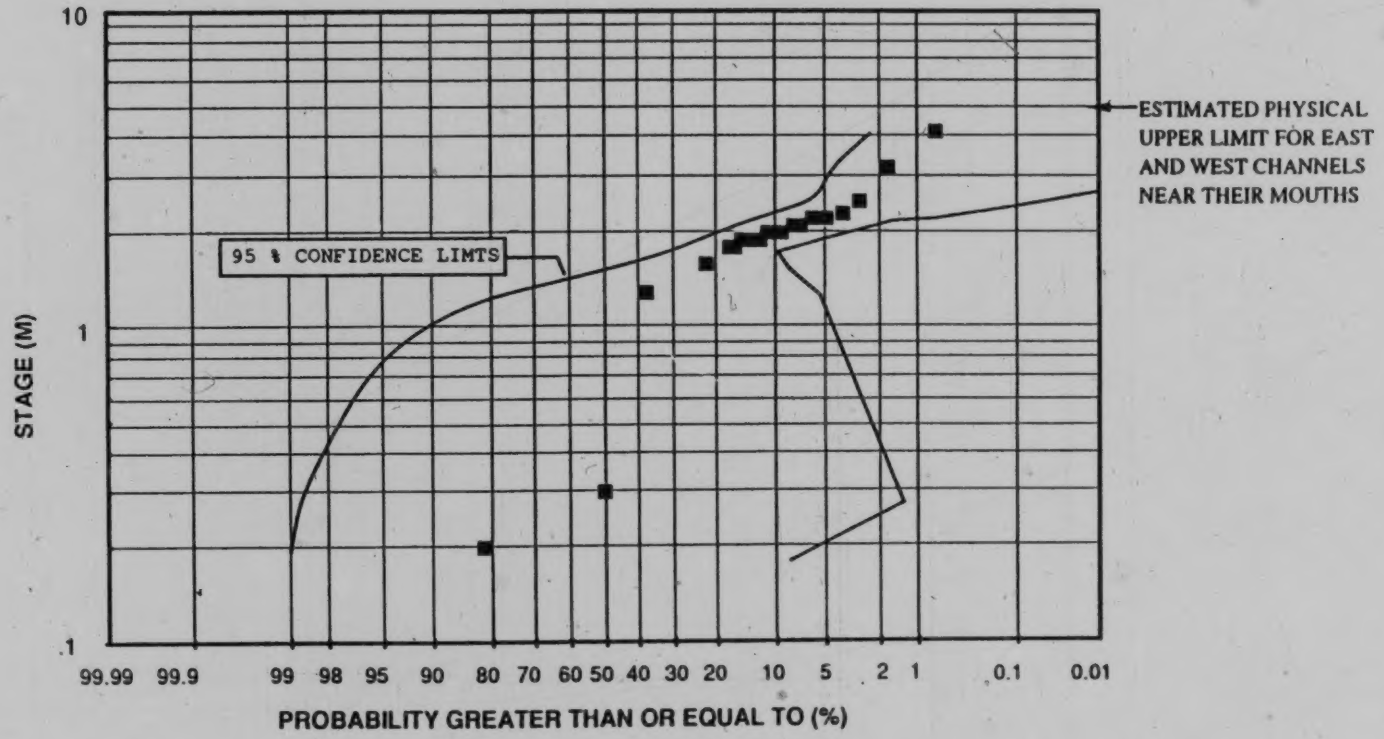


Figure 5.8 Cumulative probability distribution for East Channel near the mouth, with 95% confidence limits

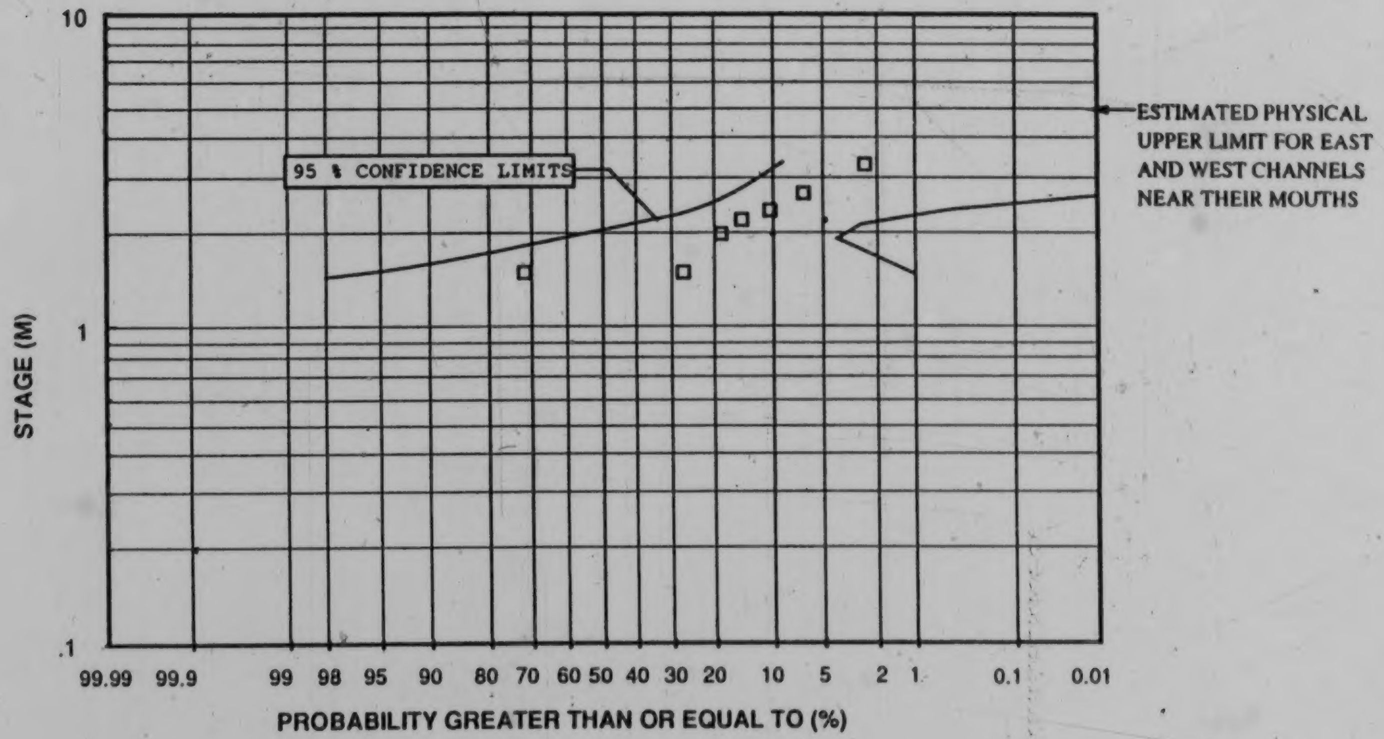


Figure 5.9 Cumulative probability distribution for the West Channel near the mouth, with 95% confidence limits

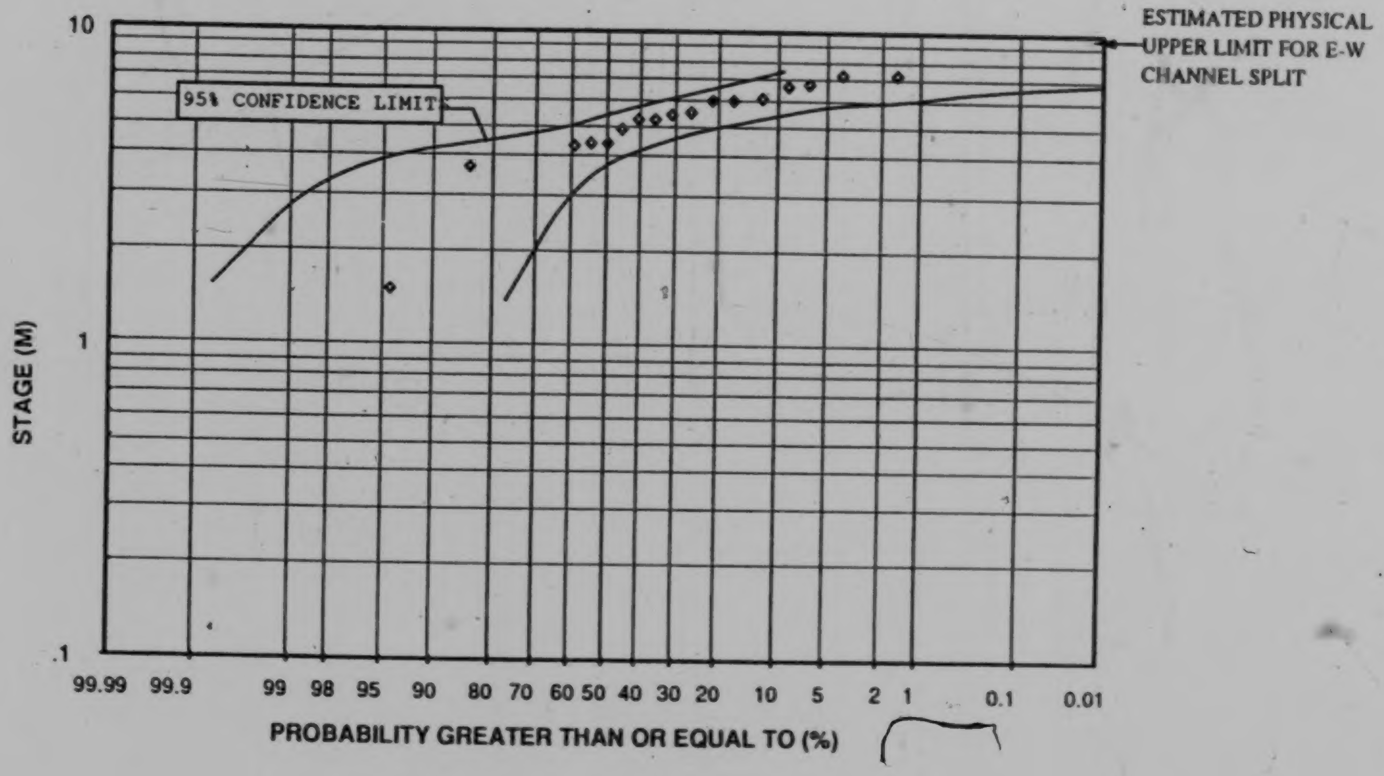


Figure 5.10 Cumulative probability distribution for the East-West Channel split, with 95% confidence limits

not evident in the probability distribution for the East Channel. Despite 50 years of record prior to 1947 and close to 40 years of record after the changes, there is no perceptible change in the water level probability distribution. Perhaps the community has simply become more aware of flood levels because of the extensive development that has taken place since 1947.

As discussed earlier the high water level at the West Channel mouth in 1985 exceeded the 1% flood level established by Environment Canada (1983) by about 1 m. Consequently the 1985 event is commonly viewed as a most unusual - even freak - event. However inspection of the historical record reveals that, even on the basis of data available up to 1983, the 1985 event had a probability of about 1.8% and was therefore somewhat *below* the 1% event, and is not an outlier.

Beyond its utility in flood plain zoning in the delta, the probability analysis puts the significance of a given water level as in the case of the 1985 level discussed above, into perspective. This was important in the analysis of the break-up observation data obtained as part of this study. From the probability distribution it was possible to discern whether the data obtained representative of a mild year, average year or severe year.

The other item needed to put the delta break-up observations into perspective is some understanding of the overall ice regime of the Hay River.

6. ICE REGIME

6.1 Introduction

The nature of the ice regime of the Hay River was determined from resident interviews and from field observations during the 1987 break-up and freeze-up, winter and break-up observations in the 87-88 winter.

6.2 Field Studies

A brief description of the observations taken during the field studies are presented below, mostly in graphical form. Detailed results are given in Appendix E.

6.2.1 Freeze-up Observations 1987

Because freeze-up events often have significant implications on ice behavior at break-up freeze-up observations were made from November 16 to 18, 1987. An item of particular interest was to see whether a pressure ridge had been formed on the lake near the mouth and, if so, to determine its nature and position. The work included ground and aerial observations of ice conditions and measurements of a profile of water levels and ice thickness on the river to determine if any unusual ice thicknesses or types were established at freeze-up and to provide data for calibration a varied flow algorithm for the delta reaches.

As shown in Figure 6.1, prior to November 16 Hay River had experienced 114.3 °C days of frost. The maximum and minimum temperatures in Hay River over the observation period were as follows: 16th, -13.6 °C and -21.7 °C; 17th, -12.3 °C and -17.5 °C; 18th -9.4 °C and -15.6 °C. The accumulated snowfall up to the 16th was 45 cm, with much of it falling just prior to the field observations as shown in Figure 6.2. October experienced above average precipitation, in Hay River total precipitation in October was 127% of normal, while in High Level it was 424% of normal.

At the time of the first flight on November 16, freeze-up had occurred from the lake up to about km 1066. The purpose of the flight was document ice conditions on the river. A recent 23 cm snowfall obscured details of the freeze-up process that would have been evident in a snow-free ice cover and likely hastened freeze-up progression. Nevertheless lodgement points during freeze-up could be observed by the rough ice which was evident through the snow.

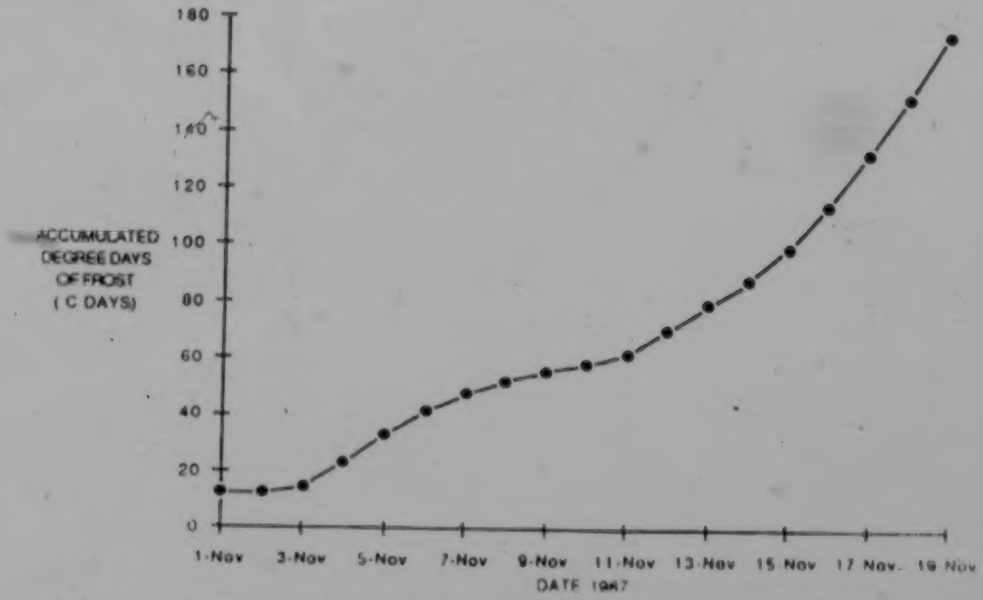


Figure 6.1 Accumulated degree days of frost at freeze-up, Hay River, November, 1987

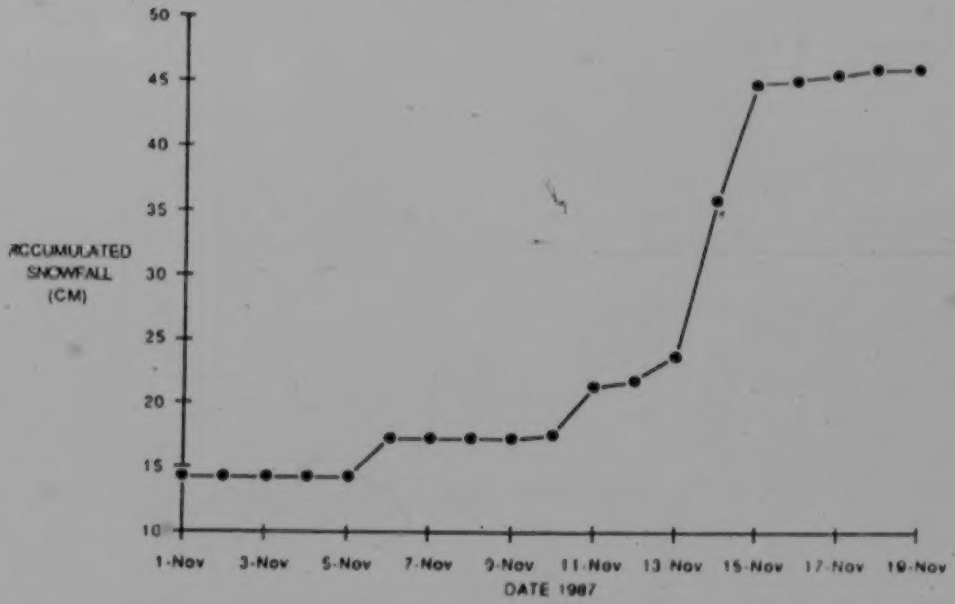


Figure 6.2 Accumulated snowfall for freeze-up, Hay River, November, 1987

Ice had apparently lodged at the upstream end of Island C-D in the East Channel (km 1111.0), as shown in Figure 6.3, with a 1.0 km pack of rough ice above this location. In the West Channel the ice lodged just downstream of the split of the Rudd and Fishing Village Channels (km 1110.60), forming a 800 m pack of rough ice upstream. In both cases the lodgement was likely against sheet ice formed over the deep water at the channel mouths. Upstream of the heads of both packs a smooth solid ice sheet extended to km 1105.45, just upstream of the high school. Rough ice, shown in Figure 6.4, extended 1.3 km above this location. Above this, smooth sheet ice, containing a number of small open water leads, extended to km 1087.4, just upstream of the golf course, where the next accumulation of rough ice occurred. A pack of rough ice extended over 21 km from this lodgement point to km 1066.4, just upstream of Paradise Garden. The pack contained numerous open leads, with some up to 400 m in length and as wide as a third of the river width. Upstream of the head of this pack the river was open to Louise Falls. In this open water section shore ice extended about a quarter of a river width into the flow from each bank and about 25% of the open portion of the river was covered with flowing frazil pans, as shown in Figure 6.5. It appeared that the majority of the frazil ice was being produced in the falls and the rapids directly below the falls.

A profile of water levels and ice thickness was surveyed from the lake to the WSC gauge site (km 1095.5), and is shown

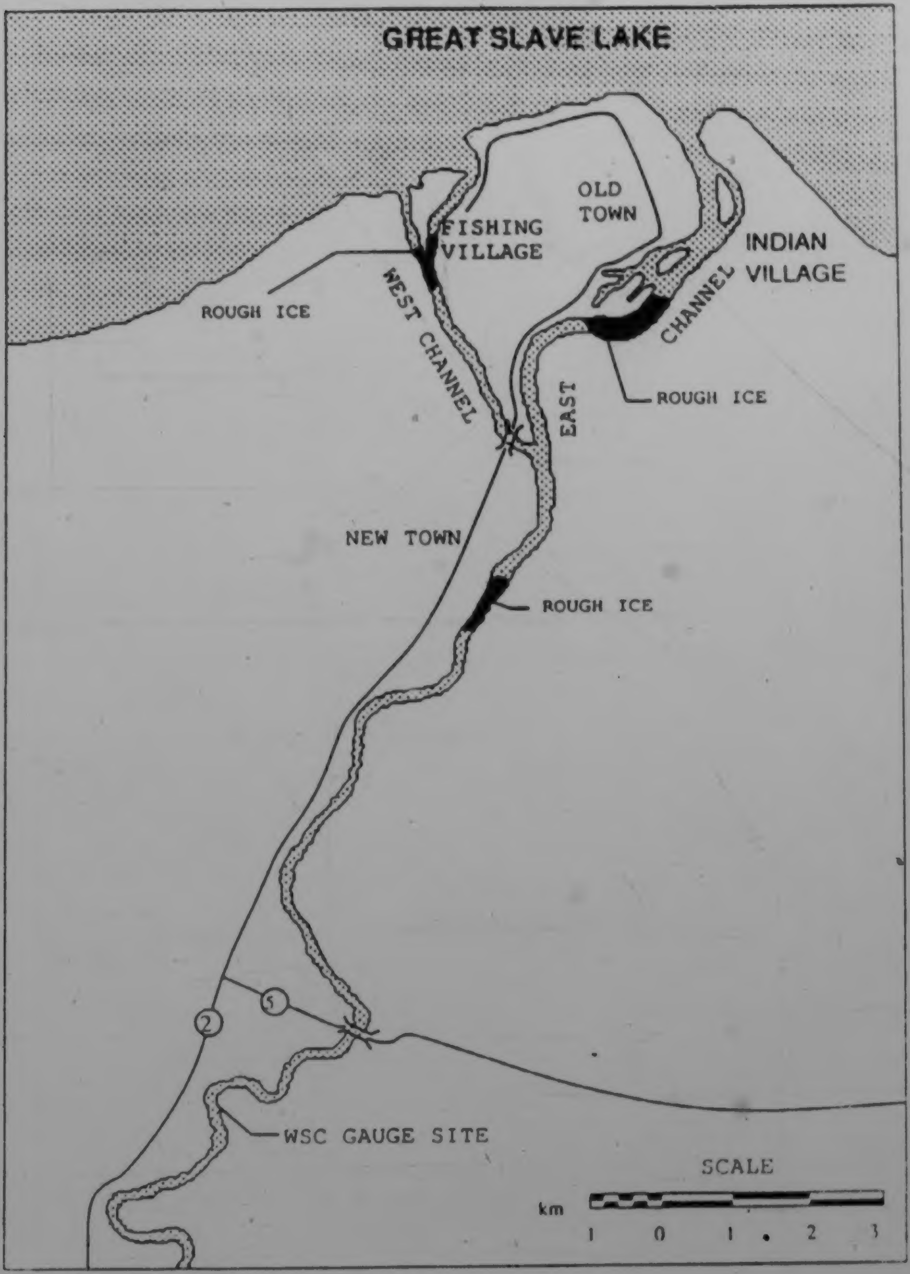

GREAT SLAVE LAKE
OLD TOWN
FISHING VILLAGE
INDIAN VILLAGE
ROUGH ICE
WEST CHANNEL
EAST CHANNEL
ROUGH ICE
NEW TOWN
ROUGH ICE
2
5
WSC GAUGE SITE
SCALE
km
1 0 1 2 3

Figure 6.3 Lodgement points during freeze-up, Hay River, 1987

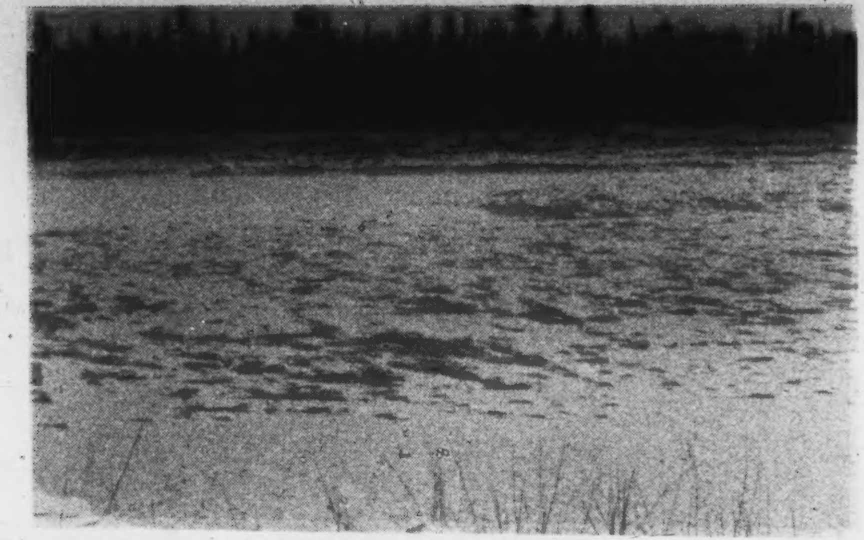


Figure 6.4 Rough ice indicating lodgement point during freeze-up, November, 1987.

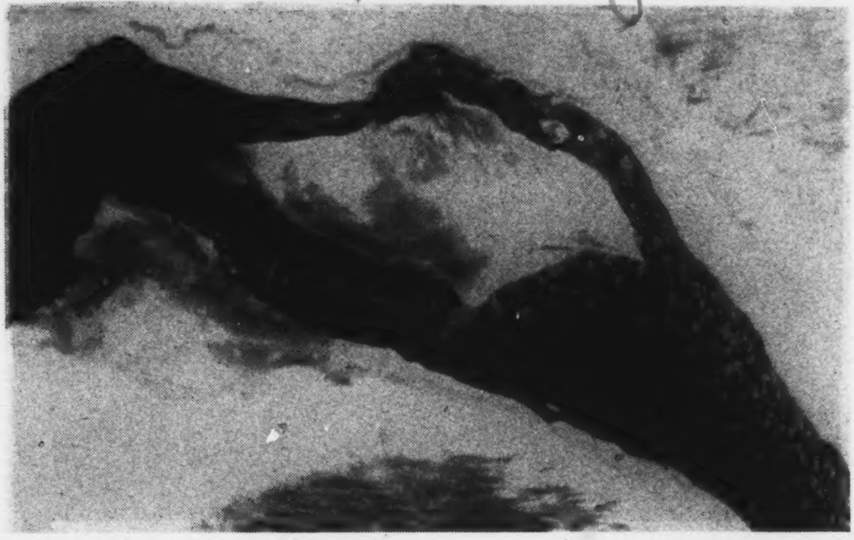


Figure 6.5 Frazil pans flowing below Louise Falls, November, 1987.

in Figure 6.6. To obtain each point on the profile, holes were augured through the ice. The water levels were surveyed and the solid ice thickness and the depth of frazil slush accumulated under the solid ice cover were measured at about 3 or 4 locations across the cross-section. These accumulations tended to correspond to the rough ice locations. The combination of the rough ice accumulation and the slush deposits could be expected to result in thicker stronger ice at break-up.

A complete cross section was taken in the West Channel just downstream of the West Channel Bridge (km 1107.89), and is shown in Figure 6.7. The channel had not yet frozen to the bottom, but little or no flow was evident.

Another objective of the freeze-up observations was to determine if a pressure ridge had been initiated on the lake near the channel mouth this early in the season. At the time of the field work shorefast ice extended for 700 m out into the lake, about the same distance offshore as a shoal that was documented in the summer surveys. Beyond this shorefast ice there were large free floating ice sheets which were about 1 km in horizontal dimension, with open water beyond. Figure 6.8 shows ice conditions on the lake in front of the town. The ice sheets were free to move so, depending on wind conditions, an open water lead could develop between the shore ice and the sheet ice. With the lead opening and closing, rubble ice would develop along the edge of the shore ice (or the bar). Also likely contributing to this rubble

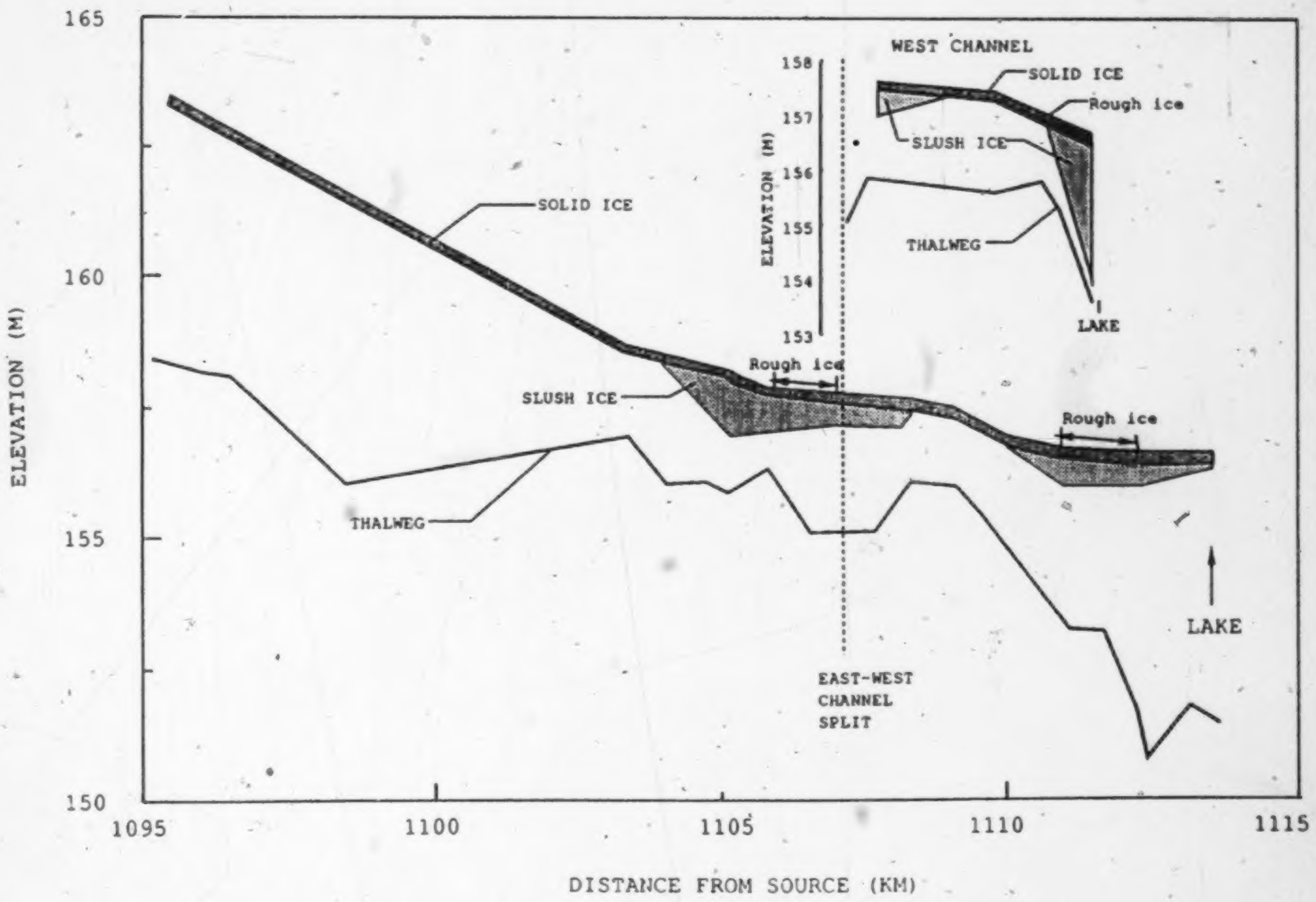


Figure 6.6. Freeze-up profiles, Hay River, November 17, 1987

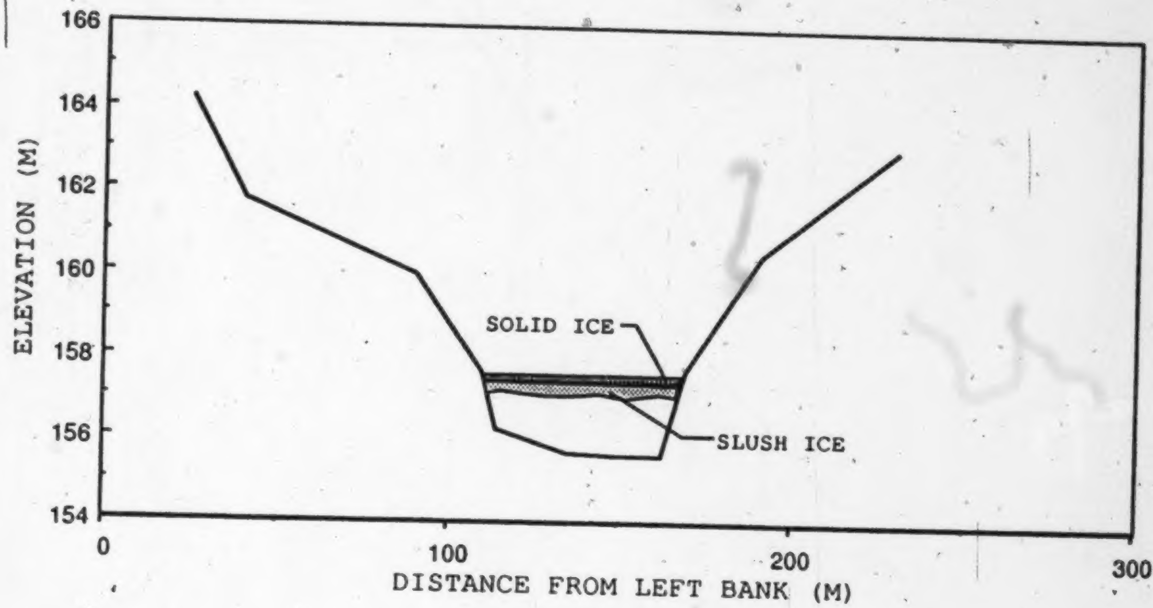


Figure 6.7 Freeze-up cross section just downstream of bridge in West Channel, November, 1987

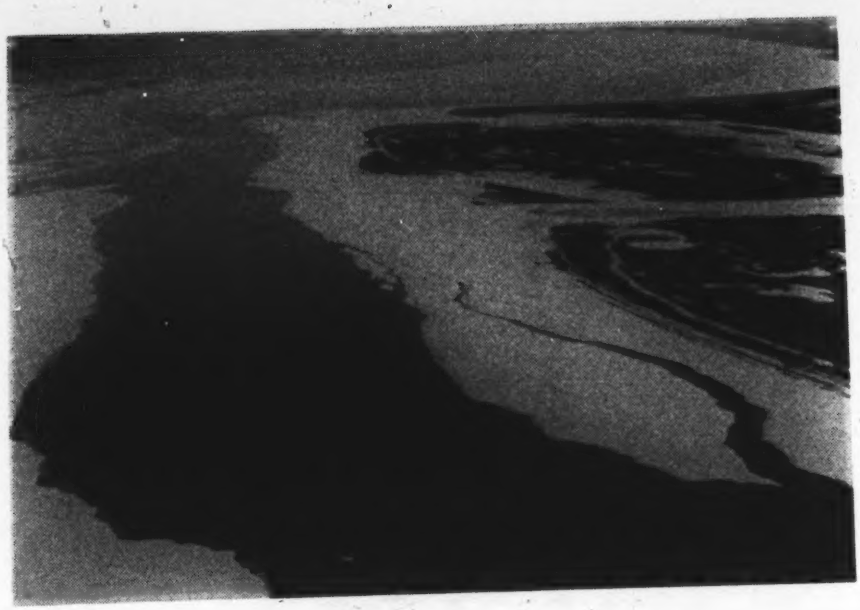


Figure 6.8 Lake ice conditions in front of Rudd Channel during freeze-up, November, 1987.

ice was frozen slush ice being driven onto the shoal by wave action. It was not possible to get out to this ridge but from shore it appeared to be already close to a metre in height in places.

6.2.2 Pressure Ridge Documentation

The pressure ridges were documented from March 7-11, 1988. Two ridges existed on the lake near the West Channel mouth at the time of the field trip. The ridge closest to shore was the rubble ice ridge which had been noted at freeze-up. This ridge was not active and is shown in Figure 6.9. The second ridge was an active pressure ridge, shown in Figure 6.10, located over a kilometre offshore.

A detailed profile of the lake ice was determined off the mouth of the Rudd Channel. This profile and the ridge location are shown in Figures 6.11 and 6.12. The locations were documented by triangulating positions on the ridges from the shore and from photos taken from the air.

It is clear from Figure 6.12 that the rubble ice formed on the offshore shoal. The height of this rubble ice in March varied from 0.8 m to almost 1.5 m. The location of the active ridge was documented but levels were not taken as it was still active and growing, with heights varying from nothing to about 2 m. This location of the active pressure

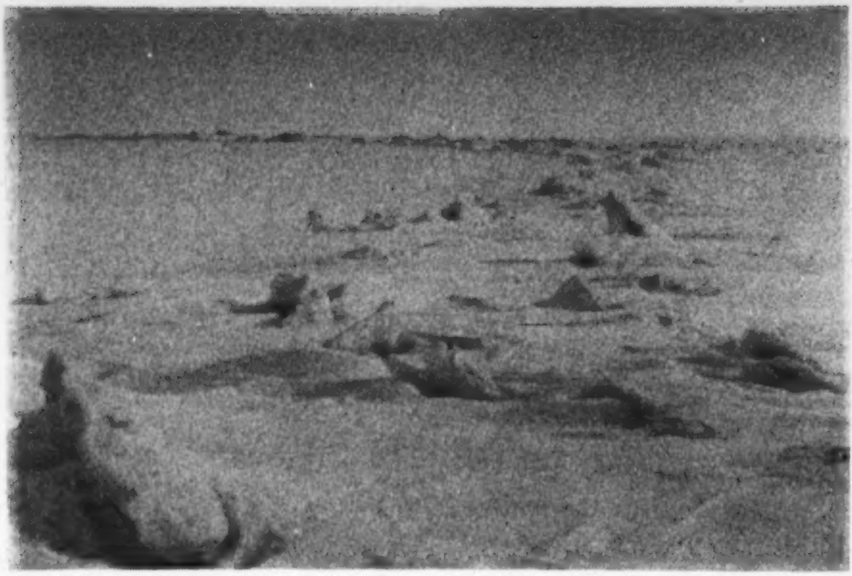


Figure 6.9 Rubble ridge formed in front of West Channel, March, 1988.

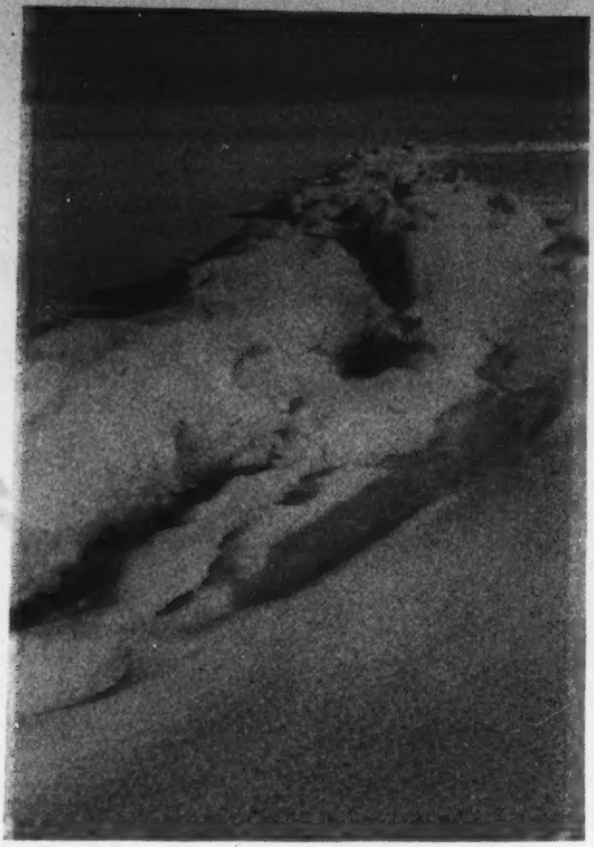


Figure 6.10 Active pressure ridge off the front of the West Channel, March, 1988.

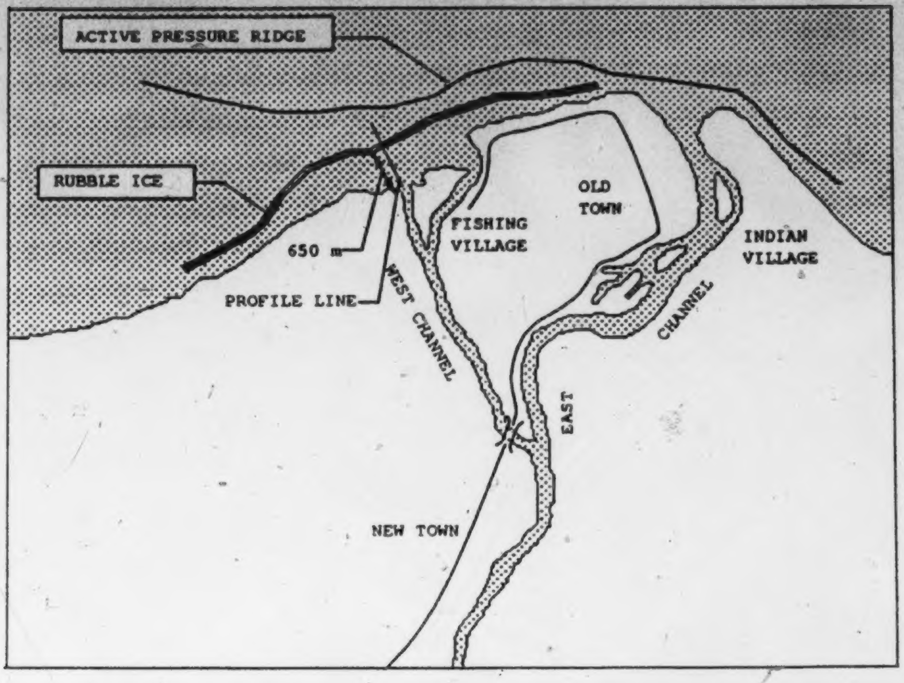

ACTIVE PRESSURE RIDGE
RUBBLE ICE
650 m
PROFILE LINE
WEST CHANNEL
FISHING VILLAGE
OLD TOWN
INDIAN VILLAGE
CHANNEL
EAST
NEW TOWN

Figure 6.11 Pressure ridge location plan March, 1988

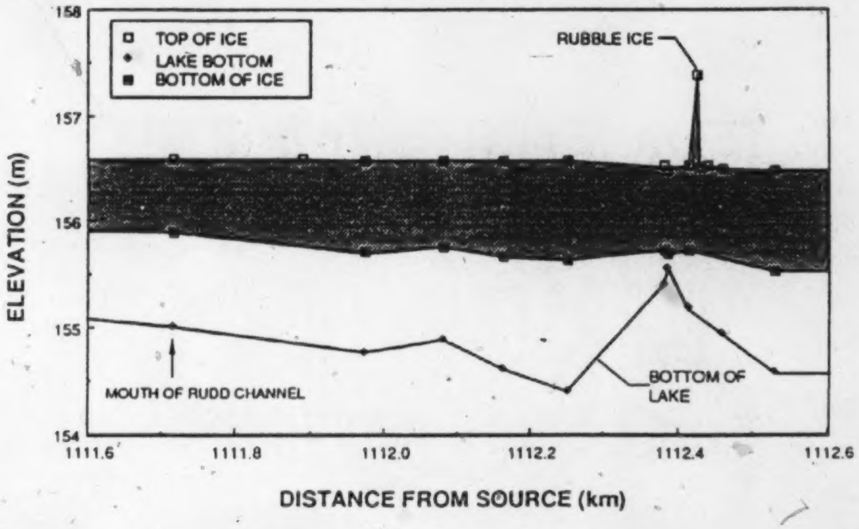


Figure 6.12 Profile in front of the Rudd Channel, March, 1988

ridge was typical in comparison to other years (Arctec, 1980).

The section of the West Channel just below the bridge was again investigated. It was now frozen to the bed across the whole width.

6.2.3 Break-up Observations 1987

Break-up observations were made from April 25 to May 1, 1987. These included both ground and aerial observations, as well as detailed monitoring of water level variations in the Town of Hay River.

A total of four flights were taken for aerial observations, the first on April 25 and the last on April 30. Two of the flights extended from the mouth of the Hay River to the confluence of the Hay and Chinchaga Rivers. Both of these flights were guided by Red McBryan who shared his experience and identified physical features and described the normal series of events leading to break-up. A third fixed-winged flight was confined to the area of the townsite. One helicopter flight was taken to inspect the pressure ridge on the lake. On all flights photographs were taken using a 35mm camera with at least one observer recording positions of the slides and other features on 1:250,000 maps.

Extensive ground observations were made from the highway, which more-or-less follows the river from Hay River to Indian Cabins. However because the area of most interest is the Town of Hay River, most ground observations were confined to this reach.

In addition to visual observations, break-up water levels were surveyed at numerous locations and times in the lower reaches of the river.

The field studies completed as part of this study were done in coperation with the government agencies sponsoring the work. The most prominant group was Water Survey of Canada who supplied personnel throughout the two break-ups observed. The personnel remained in Hay River throughout the break-up to insure proper operation of the gauge site and take actual discharge measurements where possible. As the gauge is 17 km upstream of the town, the river was open at the gauge for many of the ice jam water level profiles obtained, allowing WSC personnel to take actual measurements of discharge. were taken in the delta. This provide reliable discharge values. Normally discharge estimates are obtained from the stage rating curve at a site. During break-up constantly changing ice conditions on the river make these estimates unreliable. As personnel are not normally stationed at a site during break-up, a major source of trouble in most ice jam studies is in the estimation of discharge.

6.2.3.1 Meteorological antecedents of break-up 1987

The 1986-87 winter was relatively mild. Figure 6.13 shows Hay River only experienced 2406 °C days of frost, compared to the mean of 3140 °C days. High Level had only 2243 °C days compared to a mean of 2755. This mild winter caused ice thickness in Hay River to be somewhat less than usual and presumably partly accounts for the early break-up date of April 30.

Although temperatures were warmer than usual, the snowfall in the basin was generally above normal. As Figure 6.14 shows, snowfall in High Level was well above normal. Above average snowfall was also experienced in Fort Vermilion, where it was 127 percent of the median. The only station in the basin to show less than normal values was that at Hay River itself.

6.2.3.2 General progression of break-up 1987

Prior to break-up considerable work had been carried out on the river by Town personnel in the hope of minimizing ice jam flooding. This work included clearing the snow from the lower ends of both the East and West Channel to promote greater decay and melting of the ice. In addition, a ditch-witch was used in the East Channel to cut several long trenches in the ice. At the mouth of the Rudd Channel snow

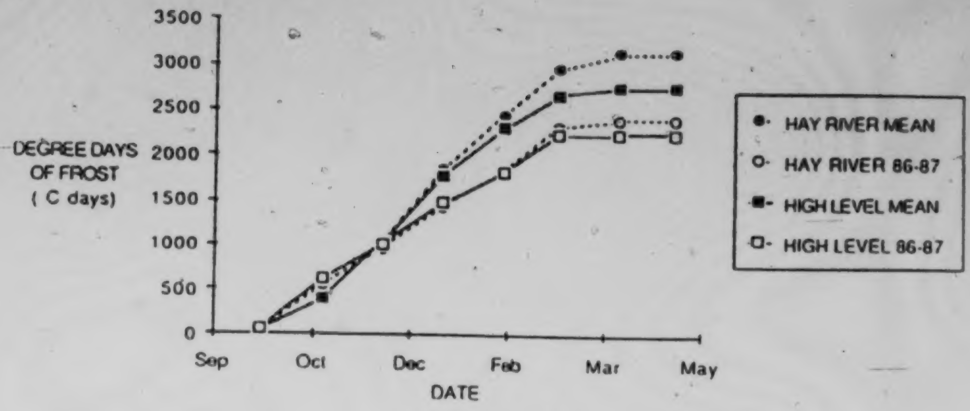


Figure 6.13 Accumulated degree days of frost over the 1986-87 winter for Hay River and High Level

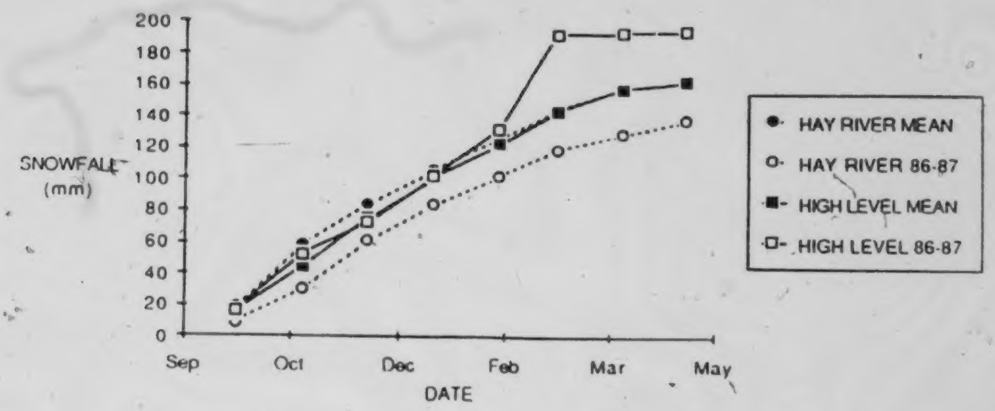


Figure 6.14 Accumulated snowfall over the 1986-87 winter for Hay River and High Level

dykes were built out onto the lake to constrain the flow in the hope that it would carry the broken ice out into the lake and prevent jamming at the mouth of the channel. These snow dykes were approximately 1.5 to 2 m in height and extended some 500m out into the lake.

When the first break-up observation flight was undertaken, on April 25, the ice cover was in place from the lake to the downstream end of the golf course (km 1092.5). Although some open water existed in this reach it was very infrequent and never extended for more than 30 percent of the river width. Upstream of this solid ice cover open water extended for 800m to the toe of an ice jam which in turn extended for 23 km to km 1069.2, near Paradise Gardens. Beyond this, open water extended through Louise Falls and past Alexandra Falls. Above Alexandra Falls numerous ice jams were present with sections of intact ice cover and small sections of open water between each jam. This series of jams extended to km 834 where the head of the last jam was located. Above this point open water existed to the confluence of the Hay River and the Chinchaga River. This was the extent of the flight but since no ice was moving in the water at this point it was presumed that no ice existed in the river upstream. A summary of the conditions observed on April 25 is given in Figure 6.15 .

On the evening of the 25th, the jam located by the golf course broke, forming a new jam with the toe at km 1104.12.

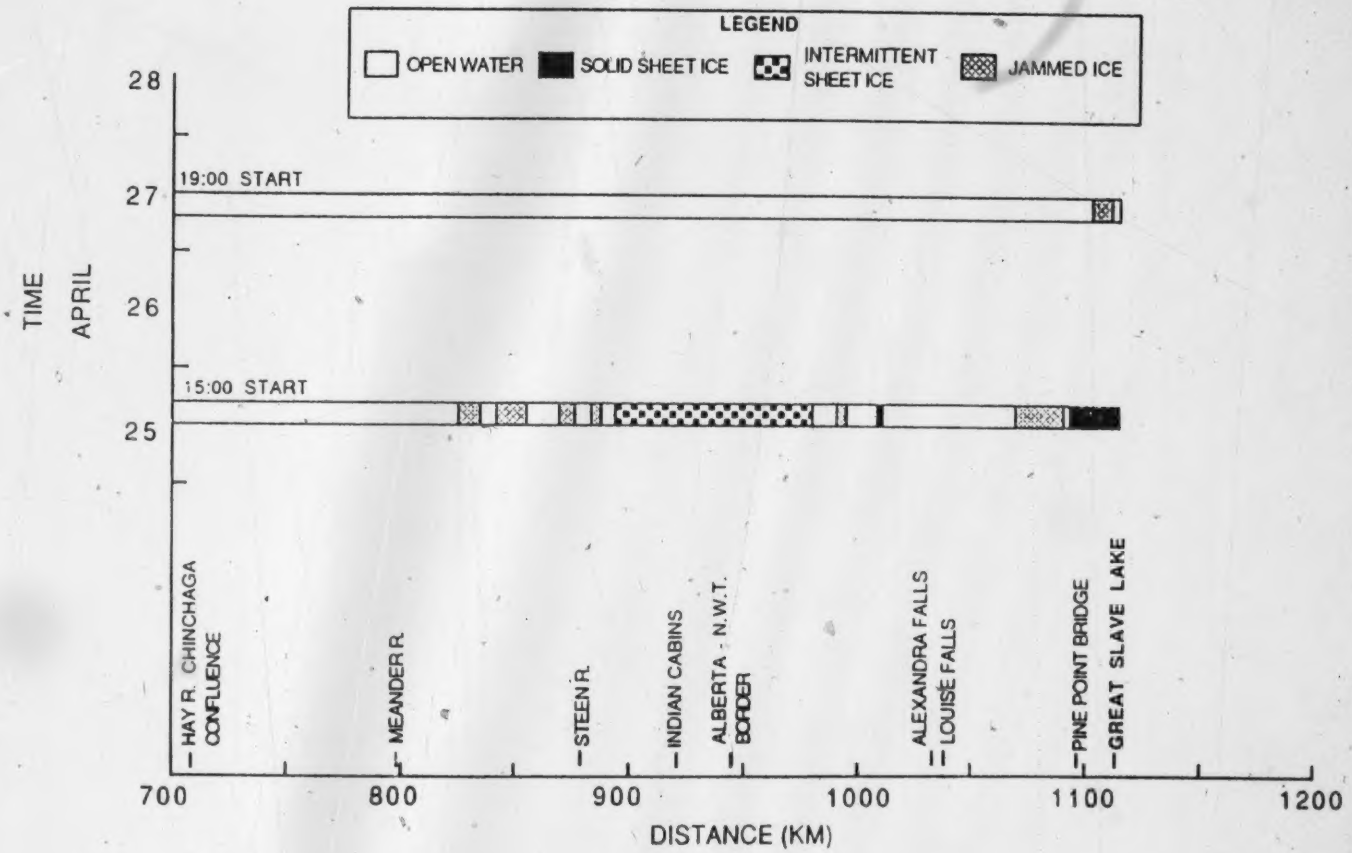


Figure 6.15 Summary of river ice conditions, break-up 1987.

On April 26 two major movements took place in this jam, which was the only one below Louise Falls. The first movement occurred at 16:20, at which time the toe of the jam moved below the East-West Channel split. In the West Channel the toe was formed 400m from the mouth of the Rudd Channel (km 1111.21), while in the East Channel the toe stopped at km 1108.3, just downstream of the split. The second movement occurred at 17:50 when the toe in the East Channel moved to just upstream of Island B (km 1111.14). The toe region of this jam is shown in Figure 6.16. No movement occurred in the West Channel during this movement in the East Channel.

Another flight up the river was taken at 19:00 on April 27. No jams other than that in town existed on the river. However it was noted water levels began to increase above Alexandra Falls (km 1034.95) and remained high to Grumbler Rapids (km 988), beyond which point the levels began to diminish. In the area of higher water quite heavy ice runs were also noted. It was thought the high levels and ice runs were probably the result of the breaking of a large jam at Indian Cabins (km 920.6) earlier in the day.

Over the next few days little movement occurred at either toe of the jam in the East and West Channels. All changes that did occur in the jam were at the head of the jam. Figure 6.17 shows a detailed summary of the evolution of the jam in the townsite area. Overnight on April 27 the ice floes noted during the flight reached the jam, building the head of the pack to km 1096.39. (At 23:00 this was at a

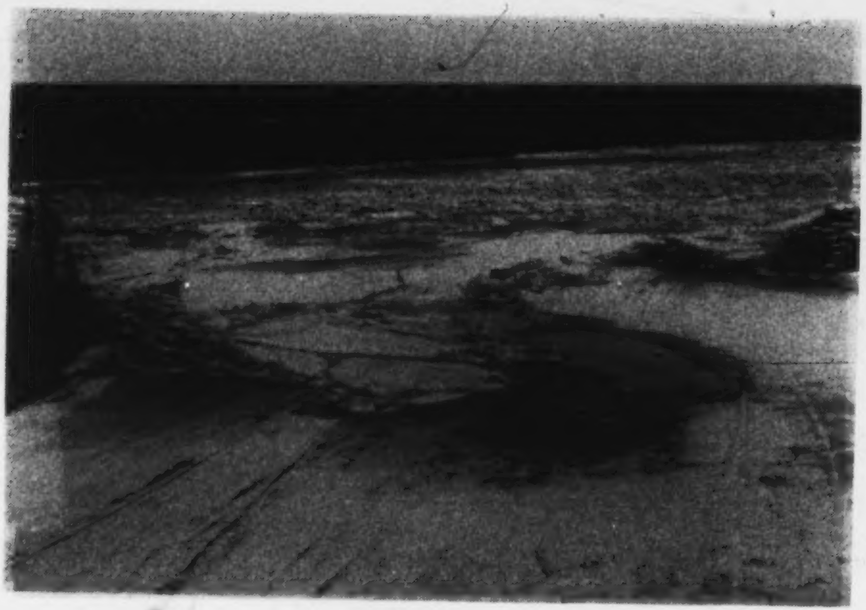


Figure 6.16 Toe of jam in East Channel, looking upstream, break-up 1987.

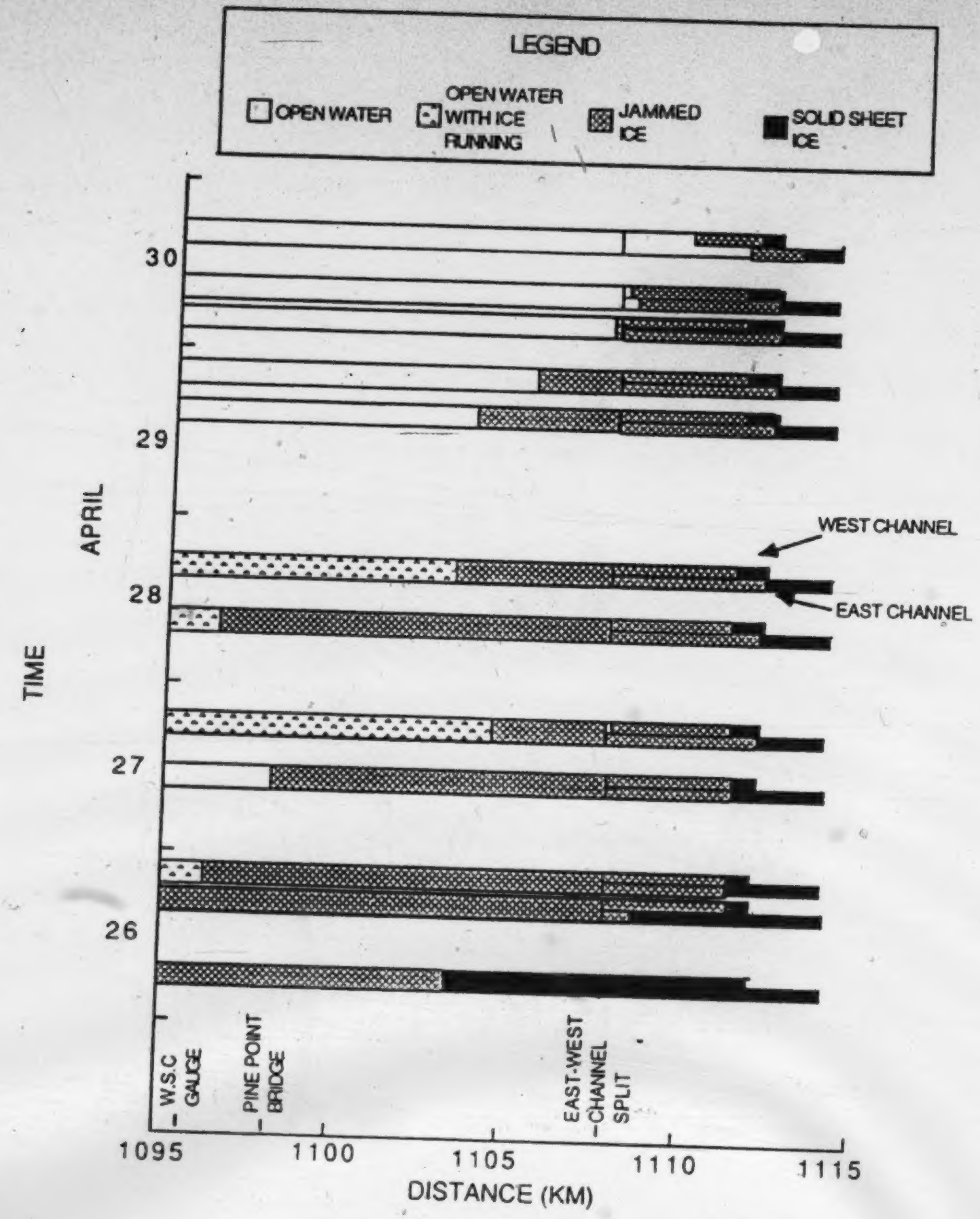


Figure 6.17 Summary of river ice conditions in delta region, break-up, 1987.

rate of approximately 3 m per minute.) By noon on April 28 ice floes had diminished and the head began to move downstream due to melting of the jam by the warm water (water temperatures of 3.5 ^{o}C and 4.5 ^{o}C were measured at Pine Point Bridge at 18:00 on April 29th and at 11:40 on April 30th respectively.).

During April 29th and 30th the head continued to move downstream due to melting. Figure 6.18 shows what was left of the East Channel jam at 12:45 on April 30. By 16:00 on April 30th, the pack in the East Channel was only 1.87 km long and at 17:00 ice began to move out into the lake. In the West Channel the head was 1.1 km below the split. At 18:00 all threats of flooding had ceased and open water existed in both the East and West Channels.

The pressure ridge on the lake played little part in the break-up. The effects of clearing the snow from the ice and cutting the ice with a ditch-witch could not be quantified, but it was noted that a large lead that developed in front of the toe of the jam in the East Channel did not follow any of the cut lines. The snow dykes on the West Channel fulfilled their purpose of carrying the flow out onto the lake ice, but their effectiveness in reducing flooding was not clear.

During the 1987 break-up water levels were noted at various locations and times from the mouths of the East and West channels upstream to km 1089.57. To do this temporary bench marks were established at various locations along the reach. These were tied into Geodetic Survey of Canada datum

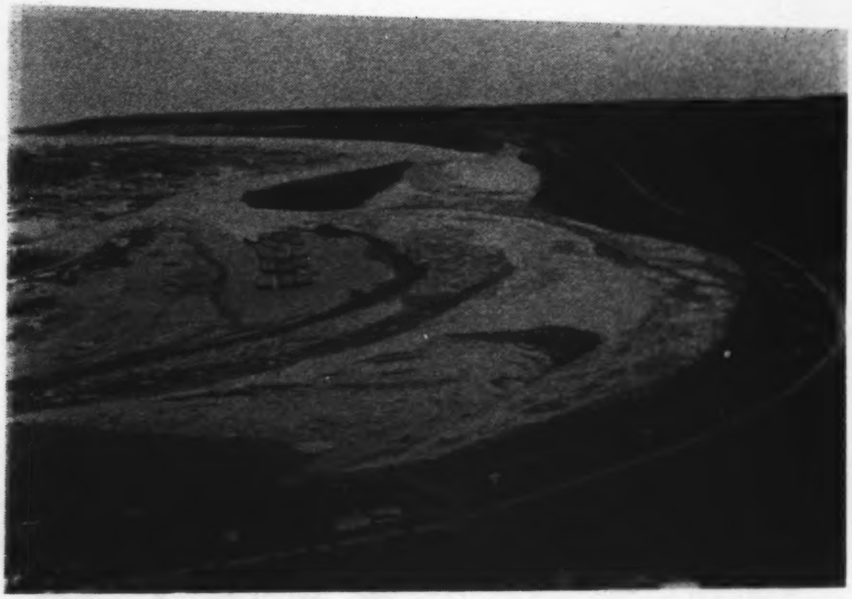


Figure 6.18 Remaining jam in the East Channel at 12:45 April 30, 1987.

during the second field trip in July. All survey circuits were closed to ensure accuracy.

Eleven sites were monitored in the East Channel, 4 in the West Channel and 7 in the river above the split. Figures 6.19, 6.20 and 6.21 show the variation in water level with distance through the East Channel and above the split at various times. Profiles for the West channel are plotted separately in Figures 6.22, 6.23, and 6.24.

Discharge variation over the break-up period is given in Figure 6.25. The peak discharge occurred on April 28 and was about 980 m^3/s. Discharge remained above 800 m^3/s from the 28th until after the ice went out

6.2.4 Break-up observations 1988

Break-up observations were made from April 23 to May 2, 1988. As in 1987, these included both ground and aerial observations, as well as detailed monitoring of water levels in the Town of Hay River.

6.2.4.1 Meteorological antecedents of break-up 1988

The 1987-88 winter was again relatively mild. Figure 6.26 shows that Hay River only experienced 2570 °C days of frost compared to the mean of 3140. In the more southern areas of

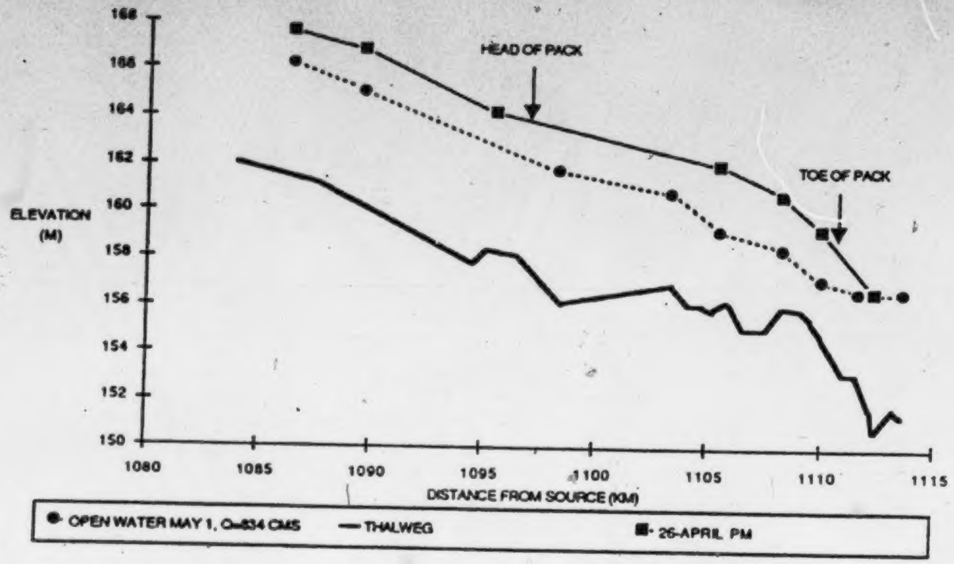


Figure 6.19 Profile, via East Channel on April 26, PM, 1987

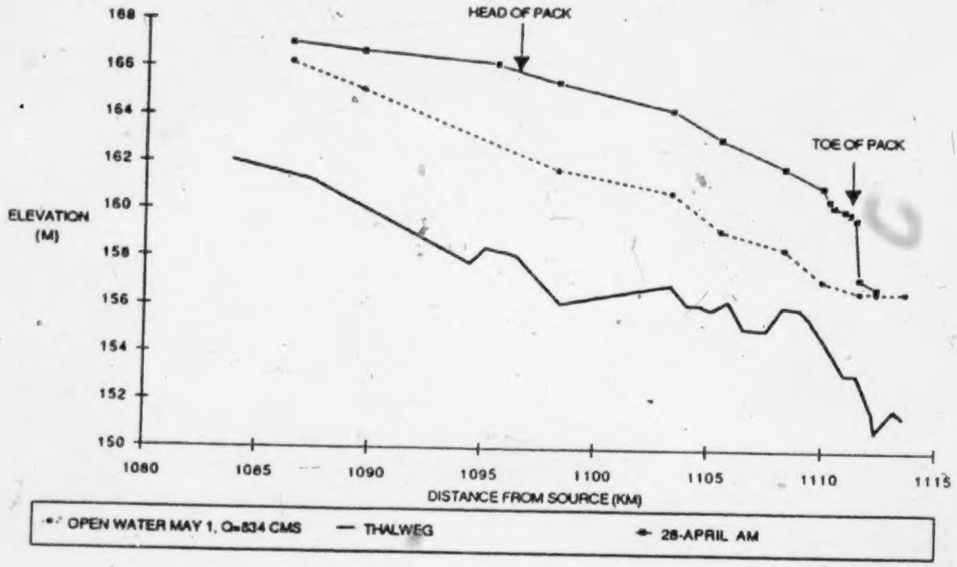


Figure 6.20 Profile, via East Channel on April 28 AM, 1987

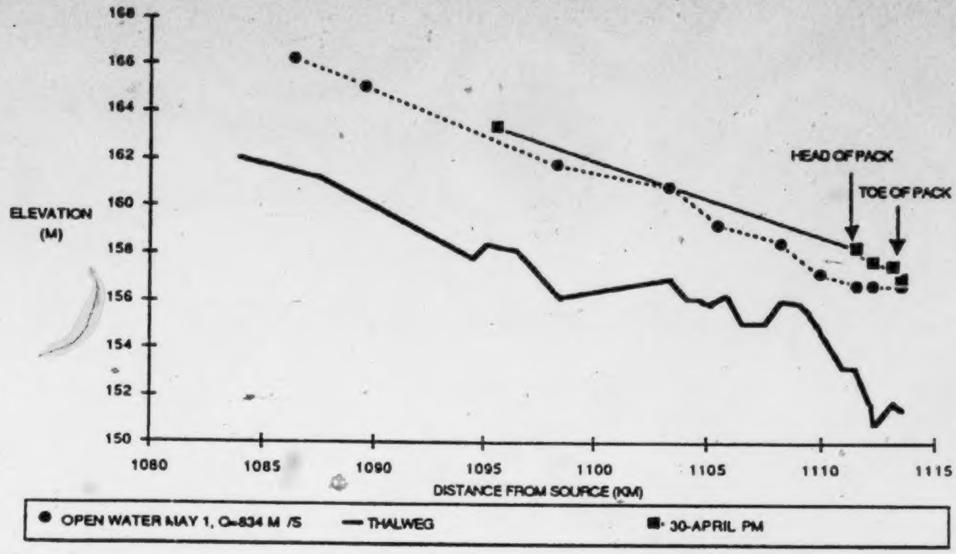


Figure 6.21 Profile, via East Channel on April 30 PM, 1987

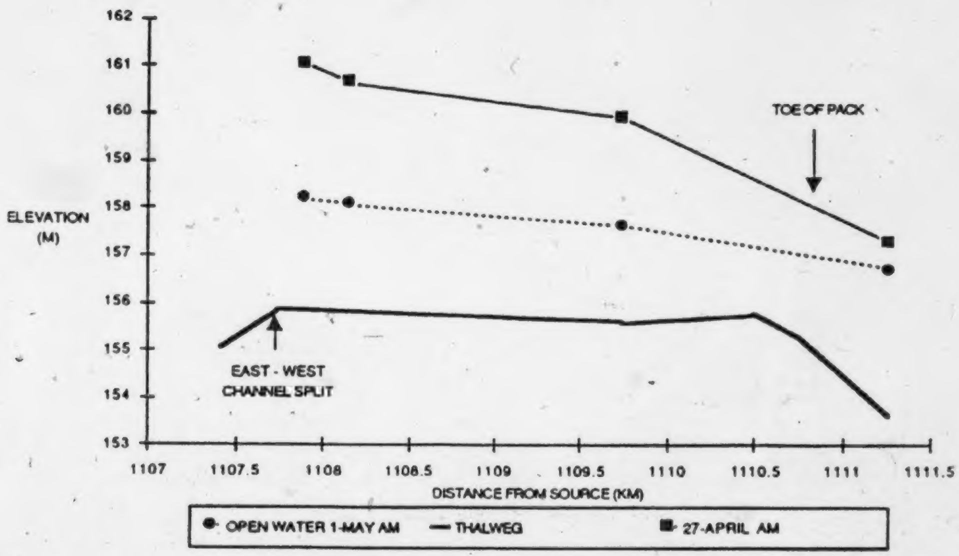


Figure 6.22 Profile,along West Channel April 27 AM, 1987.

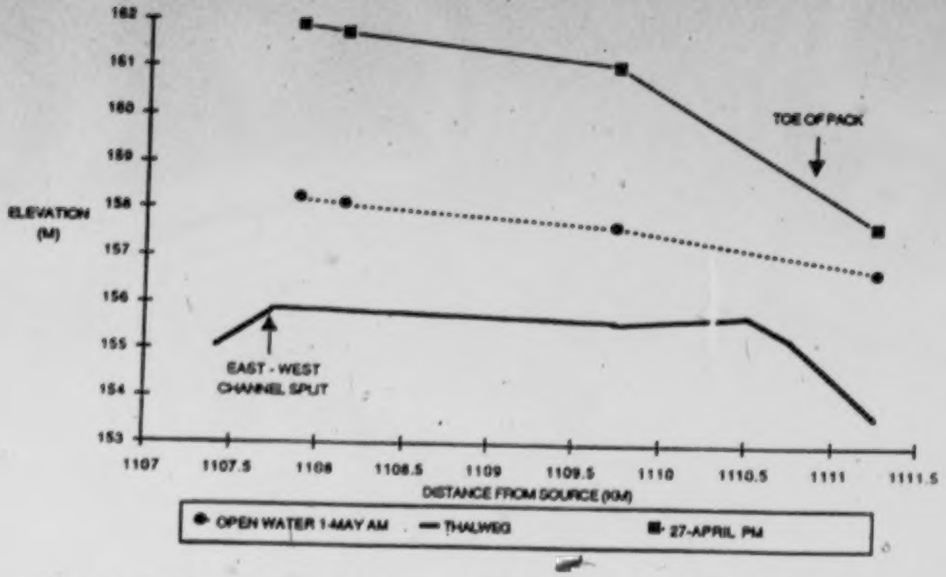


Figure 6.23 Profile,along West Channel April 27 PM, 1987.

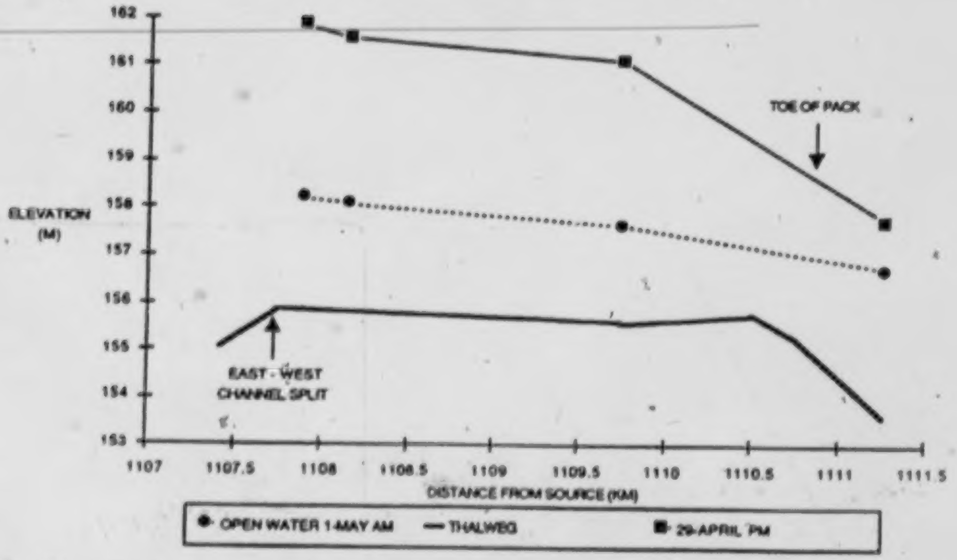


Figure 6.24 Profile,along West Channel April 29 PM, 1987.

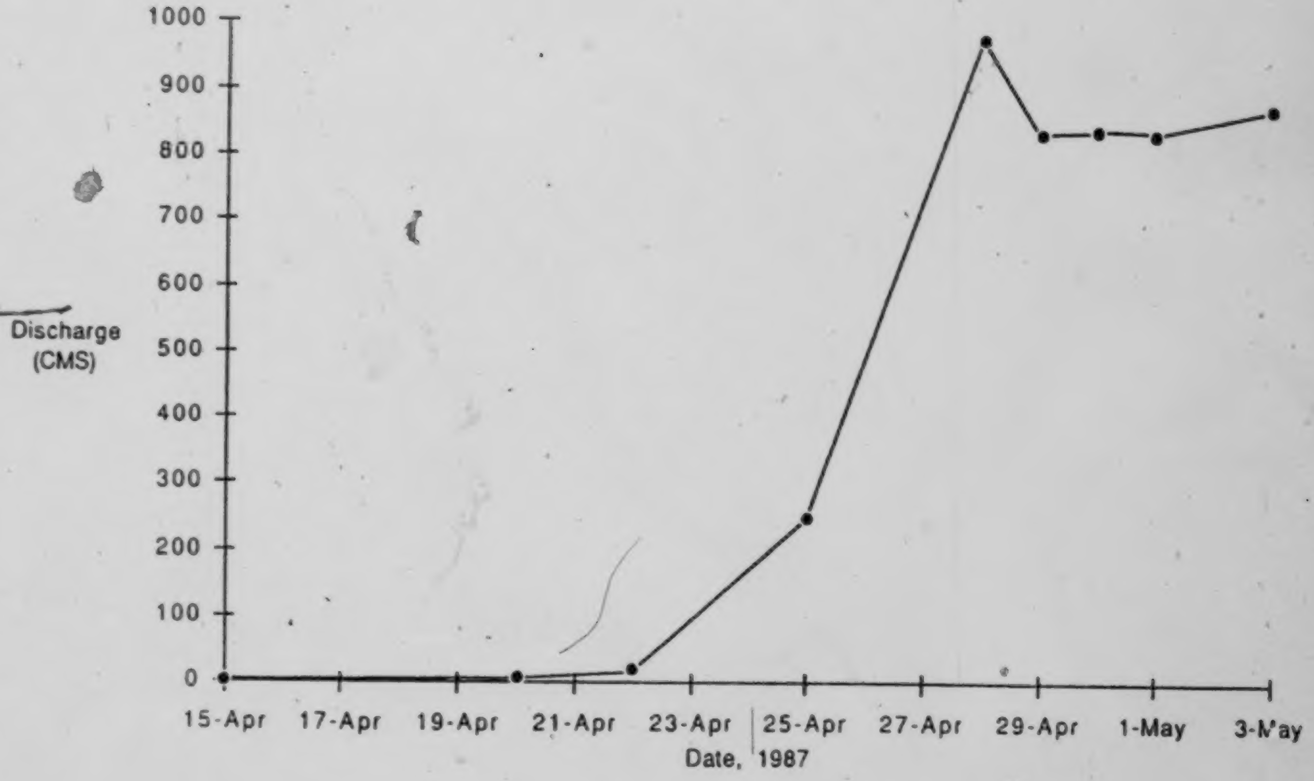


Figure 6.25 Discharge variation over 1987 break-up period.

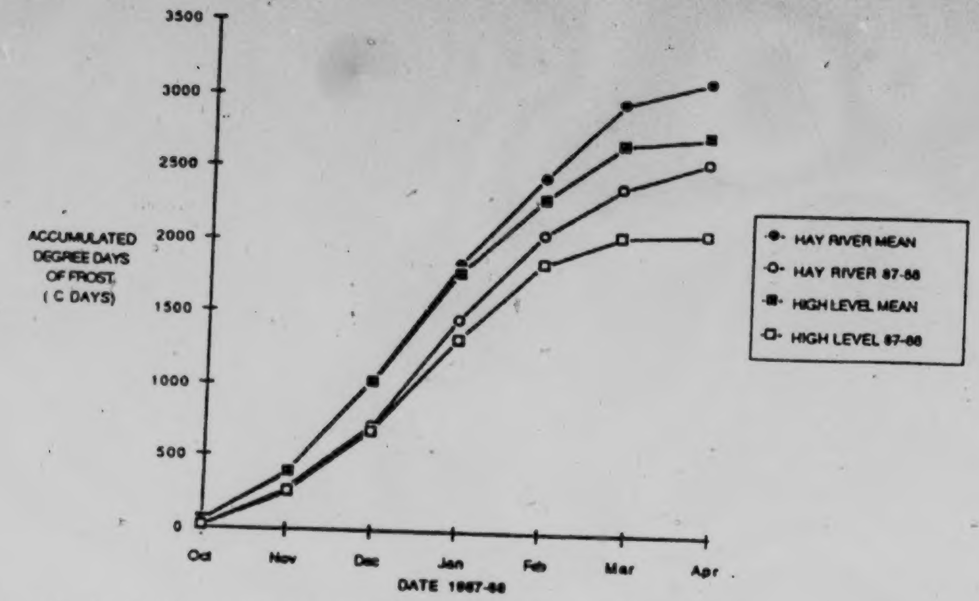


Figure 6.26 Accumulated degree days of frost for winter 1987-88, Hay River.

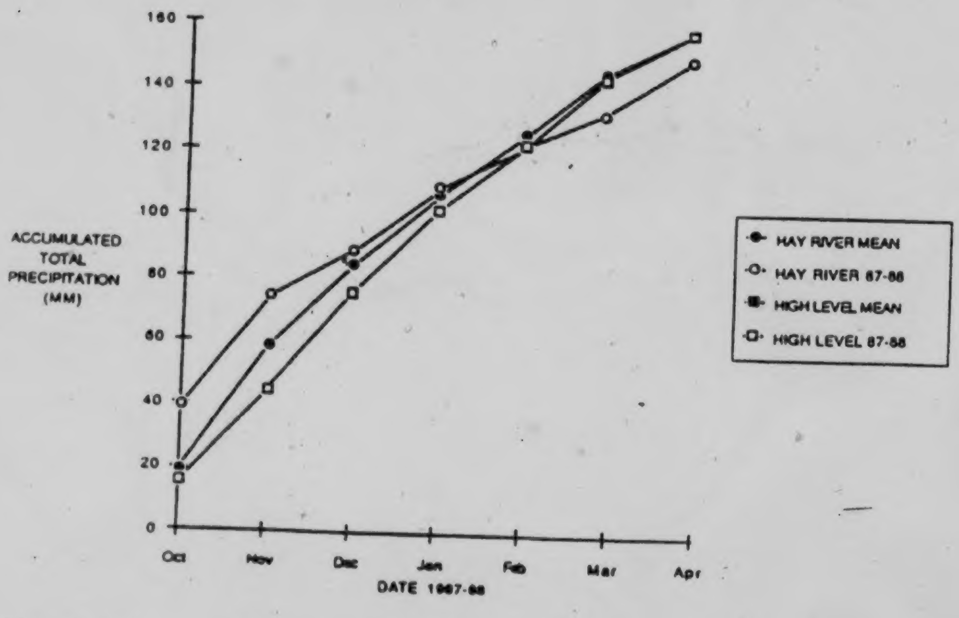


Figure 6.27 Accumulated snowfall for winter 1987-88, Hay River.

the catchment High Level had only 2080 °C days compared to a mean of 2755.

In Hay River total precipitation from October 1 was a little lower than normal, as shown in Figure 6.27. High Level experienced somewhat greater than average total precipitation, but much of this occurred early in the fall. Snow on the ground on April 1 was a little below normal.

6.3.4.2 General Progression of the 1988 Break-up

Prior to break-up considerable work had again been carried out on the river by Town personnel to minimize ice jam flooding. All of this work was done on the West Channel where snow dykes were again built out onto the lake to constrain the flow in the hope that it would carry the broken ice out into the lake and prevent jamming at the mouth. Figure 6.28 shows the location of the dykes and also the location of ice bridges that existed just prior to break-up. The snow dykes differed from those in 1987 (the first year they were used) in that one dyke was carried completely across the Fishing Village Channel.

At 15:00 on April 23 the Chinchaga River at the Highway 58 crossing (km 612.48) was open and the water temperature was 2.3 °C. At the Meander River bridge the river ice was broken but little movement had taken place. Solid ice was present both upstream and downstream of the bridge. Although

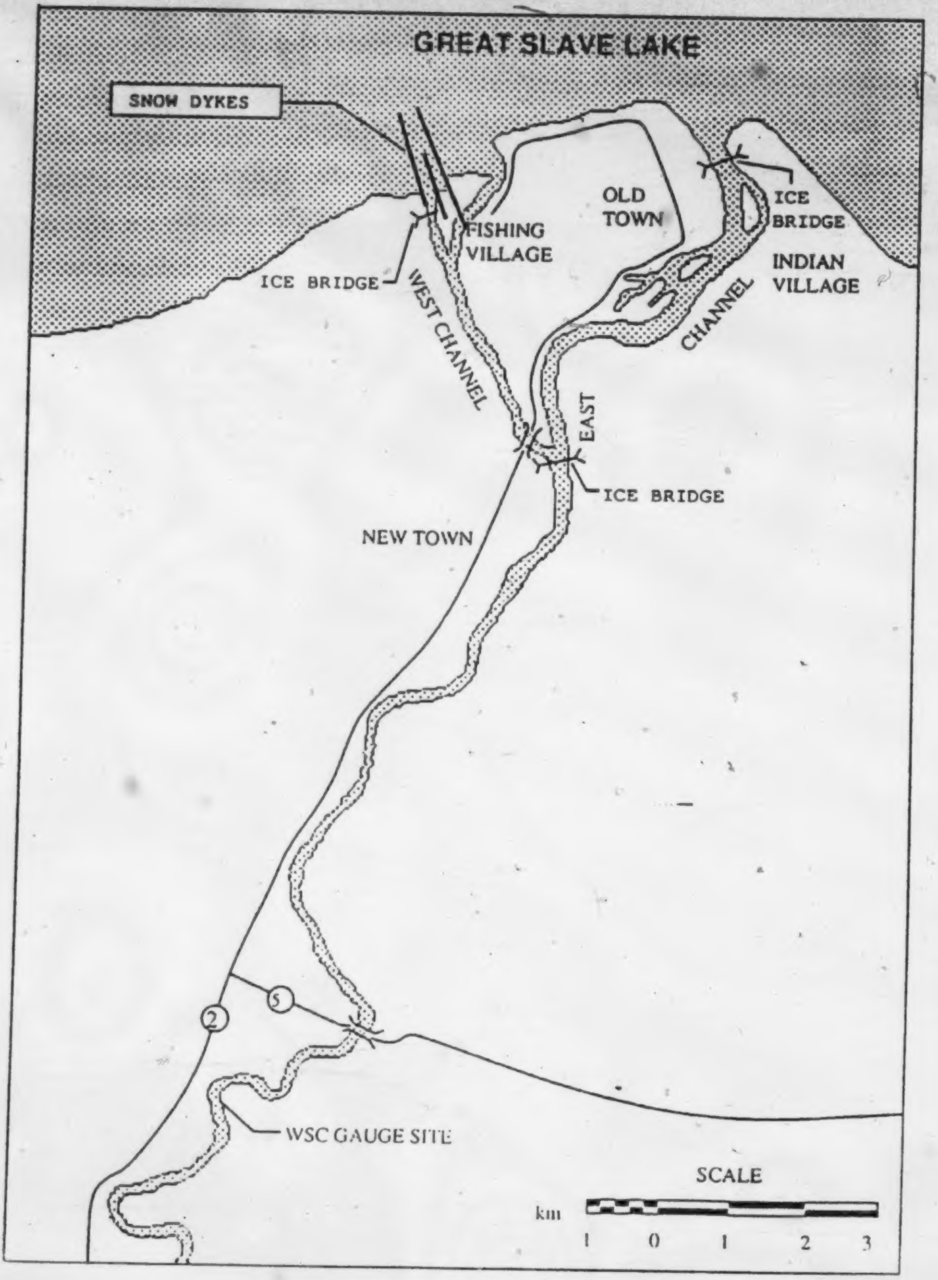

GREAT SLAVE LAKE
SNOW DYKES
FISHING VILLAGE
OLD TOWN
ICE BRIDGE
INDIAN VILLAGE
ICE BRIDGE
WEST CHANNEL
CHANNEL
EAST
ICE BRIDGE
NEW TOWN
2
5
WSC GAUGE SITE
SCALE
km
1 0 1 2 3

Figure 6.28. Location of snow dykes and ice bridges in Hay River, Spring 1988

increased discharge from spring melt had caused stages to rise, in Hay River solid ice existed through the Town except in the West Channel: the increased stage had caused water to flow over the bottom-fast ice in the West Channel to the lake. The depth of flow over the ice at the West Channel bridge was estimated to be 0.5 m.

The ice conditions observed in the reach below the falls from the ground and their development over the break-up period are summarized in Figure 6.29. On April 24 the bottom-fast ice in the West Channel began to release from the bed and float to the top. This created a juxtaposed ice accumulation in the West Channel. The river upstream of the town was open between Alexandra and Louise Falls and for about 7 km upstream of Alexandra Falls. Below Louise Falls a small 2.8 km long jam was present. Below this jam a solid ice sheet covered the river. Small open water leads existed at Pine Point bridge (km 1098.26) and at the WSC gauge site (km 1095.50).

During the night of April 24-25 ice moved below Louise Falls. By 09:30 the river was open for 4.1 km below the falls. An ice jam existed below the open water section, with its head just downstream of Enterprise (km 1041.38). The jam was 14.0 km long with the toe at km 1055.42. Directly below the toe a 400 m lead had developed. There was no change evident in ice conditions below this jam. These conditions remained constant during the day.

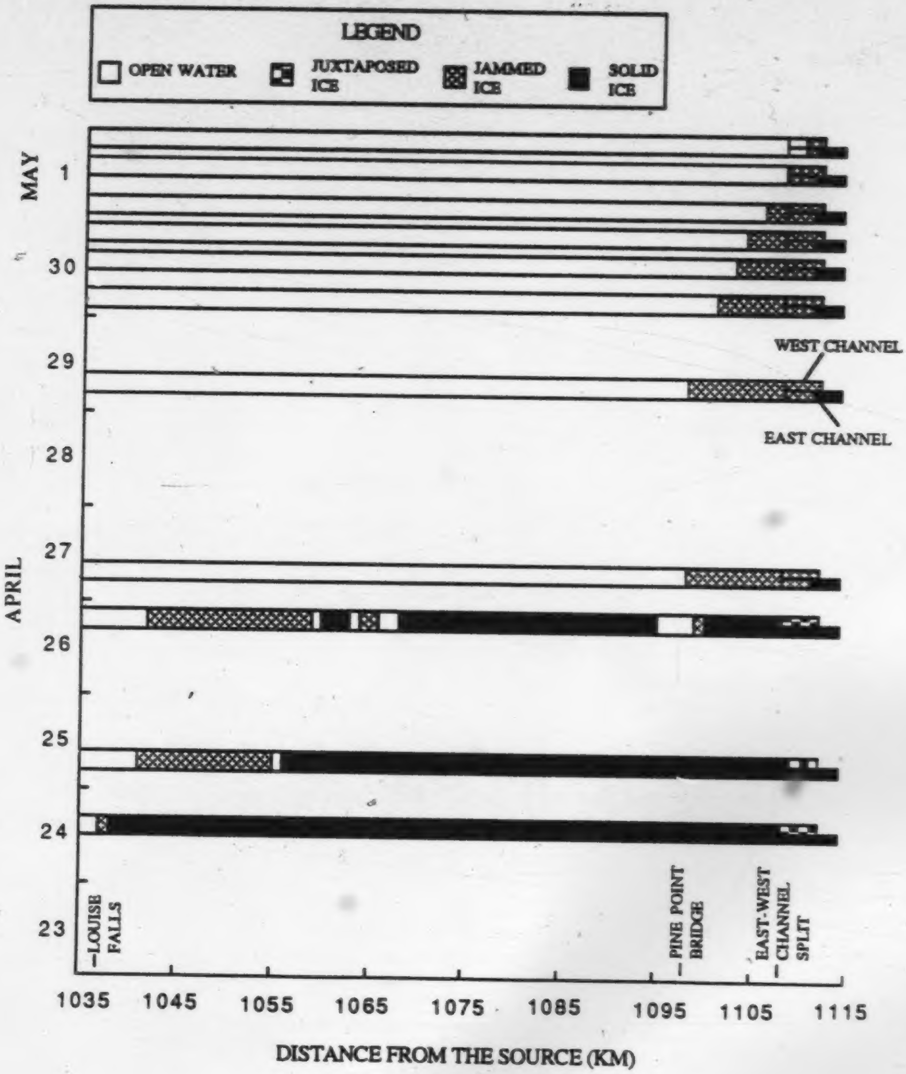


Figure 6.29. Progression of break-up, Hay River, 1988

By the morning of the 26th the head of the jam had moved downstream 1.33 km so that open water existed from Louise Falls to km 1042.65. The toe of this jam had moved 4.1 km to km 1059.52. There was again an open water lead of about 500 m downstream of the toe. Some movement had occurred overnight in the ice cover downstream of this jam. A short jam 2.2 km had formed with its head at km 1063.02 and its toe at km 1065.27. At km 1066.97, just upstream of Paradise Gardens, there was 1.08 km of open water. Below this a solid ice sheet existed to km 1095.39, near the WSC gauge site, where there was another stretch of open water 2.25 km in length. Downstream of this open water was another short jam 500m long with its toe against solid ice. The solid ice extended to the lake.

A large scale movement began early on the morning of the 27th. Ice in the town began to break-up at 07:00. Ice broke down the East Channel to the upstream end of Island C-D (km 1110.9), where the toe of a jam formed. In the West Channel ice moved through the Rudd Channel and out into the lake with the run breaking through the lake ice along the shore for about 2 km to the west of the channel . As shown in Figure 6.30 and Figure 6.31, at the end of the run ice had fanned out on and through the lake ice for a distance of about 1 km from shore. In the Fishing Village Channel the toe of the jam had formed at the mouth of the channel. The head of the jam was located at km 1098.40, close to Pine Point Bridge. Above this jam the river was open all the way to the falls.

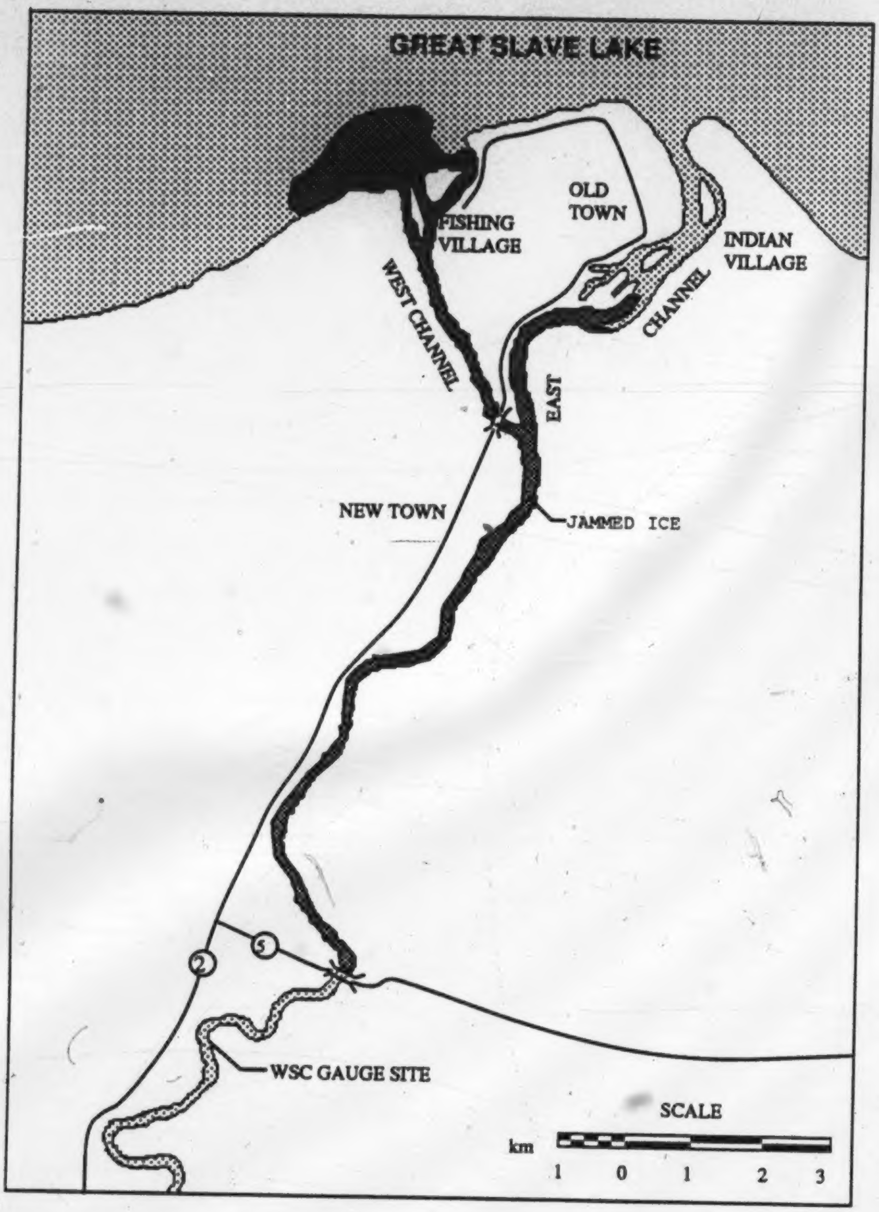

GREAT SLAVE LAKE
OLD TOWN
FISHING VILLAGE
INDIAN VILLAGE
WEST CHANNEL
EAST
CHANNEL
NEW TOWN
JAMMED ICE
②
⑤
WSC GAUGE SITE
SCALE
km
1 0 1 2 3

Figure 6.30. Location plan of ice jam, Hay River, April 27, 198

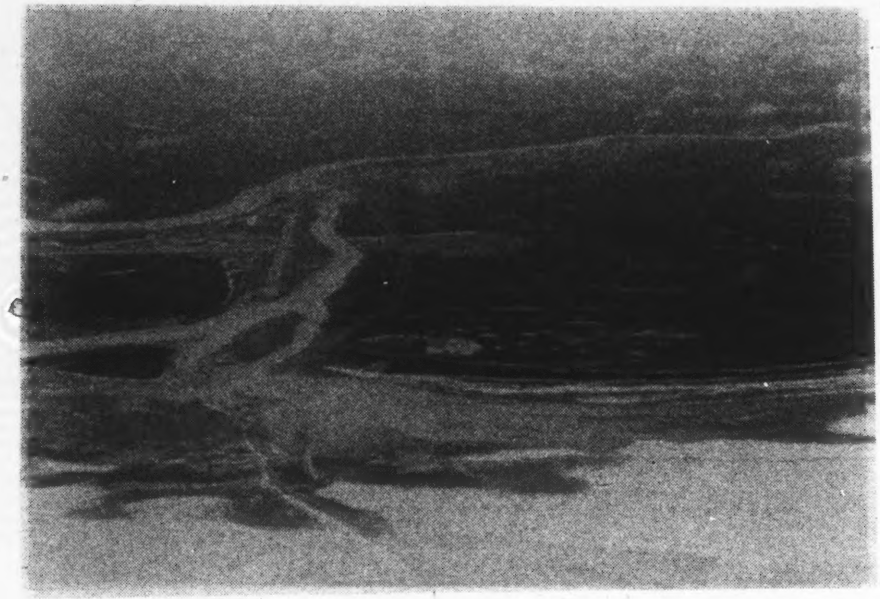


Figure 6.31 Ice fanned out on the lake in front of the Rudd Channel, break-up 1988.

There was no change on April 28. Air temperatures decreased such that the mean daily temperature for the 28th was below zero. With the cold temperatures the discharge in the river decreased causing water levels in the town to fall steadily. Over the night of 28th-29th the head of the jam moved upstream to km 1097.6. Although air temperatures were cold in Hay River, they seemed to be the result of cold north winds off the lake. In the upper catchment air temperatures remained above zero. This caused water temperatures to increased a little from 0.0 °C to 0.3 °C at the head of the jam. Due to melt caused by the above zero water temperatures the head began to move downstream during the day and by 22:00 the head was at km 1098.46. At 07:30 on April 30th the head was at km 1098.46 and by 22:00 was at km 1104.46.

The jam continued to melt overnight and by the morning of May 1 the head was below the East-West Channel split. The toes had still not moved in either channel, but a large open water lead about 700 m long and 150 m wide had formed in front of the toe in the East Channel. At 22:45 the toe in the East Channel moved, filling this open water lead. It stopped when it hit the solid ice at the front of the lead. By this time, with the warm water continuing to melt the ice, the ice jam in the East Channel was less than 500 m in length.

By the morning of the May 2 the ice jam in the East Channel was almost completely melted, with just a solid ice cover from the downstream end of Island C-D to the lake. In the West Channel there was still a short jam on the Rudd Channel and the Fishing Village Channel.

The discharge variation over the break-up period is plotted in Figure 6.32, where the normal rapid rise in the hydrograph is evident. The peak discharge, 750 m^3/s, was reached late on April 27. Discharges could have risen higher than this had air temperatures remained warm. As it was daily mean temperatures dropped to just above 0 °C from the 27th to May 1. This colder weather slowed down the melting process and hence the discharge. If temperatures had remained warm there would have been a significantly greater chance of flooding.

Water levels were again surveyed and are shown in Figure 6.33.

6.2 General ice regime

With only one year of observations it was important to collect all other available information on ice processes at Hay River. The field studies provided the perspective required for interpreting the historical data, which was mostly qualitative. From the historical data, information on normal ice processes as well as extreme event ice processes was obtained. The historical data in combination with the field data provided a good understanding of the mechanisms

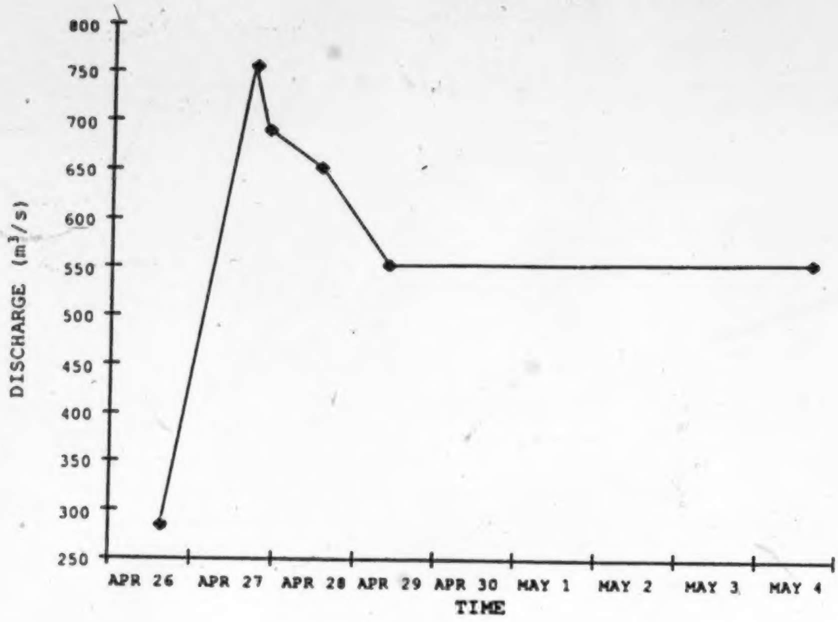


Figure 6.32 Discharge measurements by WSC during break-up, Hay River, 1988.

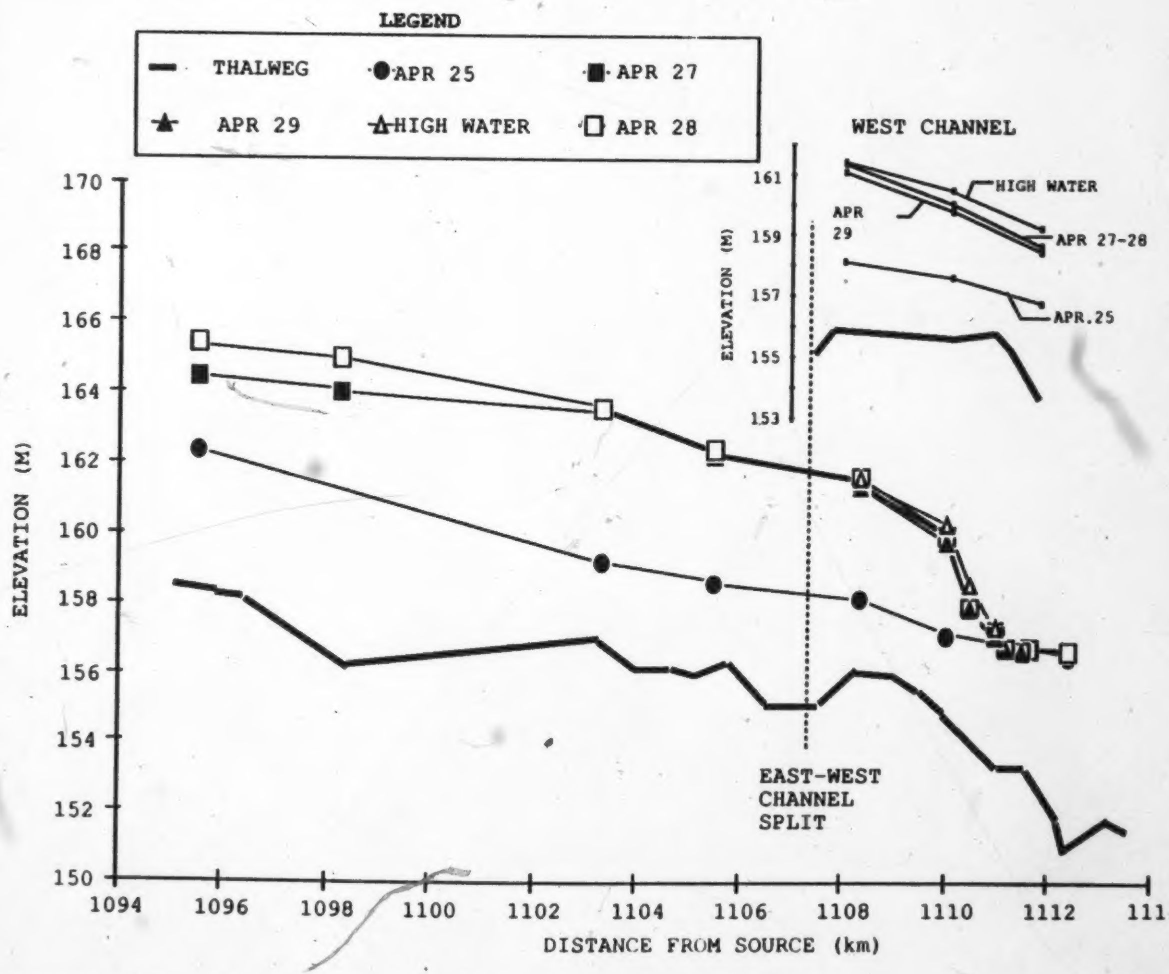


Figure 6.33 Break-up profiles, Hay River, 1988.

involved in the ice regime of Hay River.

The lower reaches of the Hay River typically freeze over in early November. Areas of relatively mild slope above the falls and in the delta regions are the first to freeze with the steeper sections between the falls and below Louise Falls freezing some time later.

By late winter ice thickness will reach an average of 1.0 m on the river and 1.3 m on the lake. The West Channel, being much shallower than the East Channel, freezes to the bed except over the deep sections in the two arms near the mouth.

Freeze-up processes of the Hay River seem not to influence events at break-up as much as has been noted at other sites. The majority of ice jam studies have been done along relatively continuous rivers (e.g. Dawson, Yukon and Fort McMurray, Alberta). In such circumstances any abnormalities in the ice cover caused by freeze-up and frazil ice deposition can have implications at break-up. However, in Hay River the governing factor in break-up behavior is the rapid change in the river morphology as it enters the delta region. The effect of this rapid change in morphology seems to out-weigh any abnormalities that occur during freeze-up on the river.

The freeze-up process that may have the greatest effect on break-up processes is the freeze-up of Great Slave Lake at the mouth of the river. Freeze-up begins on the lake about the same time as the river but it is not until mid-December that the lake completely freezes over. Past studies (UMA, 1979 and Arctec, 1980) and residents have made reference to ridges that form on the lake just offshore from the mouth of the river and the obstruction they may pose to passage of water and ice from the river at break-up. This tends to be a more serious problem in the West Channel as the flow moves out of this channel on top of the ice.

With only one year of observations it was not possible to carry out an in-depth appraisal of the pressure ridge regime in the vicinity of Hay River, but two mechanisms of ridge formation were documented. During freeze-up a 'frozen slush/rubble' ridge forms along the outer edge of the bar off the West Channel mouth. In the 1987-88 winter it varied in height from 0.8 to 1.5 m high. It seems to have been caused by the action of waves and large, but thin, ice floes on the bar at freeze-up. The indications are that in late winter the lake ice is bottom-fast over much of the bar.

The second mechanism forms a true active pressure ridge and is the result of thermal forces in the lake ice. This active ridge is further offshore than the rubble ice ridge.

Break-up begins on the Hay River between mid-April and early May as the discharge begins to increase as a result of snowmelt. The reach of the river below the falls breaks-up first. This run usually stalls and sets up a jam with the toe in or near the shallows of the East Channel, opposite Island C-D (km 1111), with the pack extending well upstream of the town. The water level increases at the split (km

1108.3) as the break-up front passes, so diverting water and much of the ice down the West Channel, which acts as a 'high-level by-pass' channel. Generally the flow moves down over the bottom-fast ice in the West Channel to flow out onto the lake ice and stall, forming a jam that extends back-up to, and into, the main channel above the split. (As mentioned it is commomly believed that the run stalls against the rubble and/or pressure ridges. However after observing the ice going out onto the lake during the break-up observations it is believed that, while the ridges no doubt exacerbate the problem, it is likely the run would stall in about this location whether a ridge was present or not, as the water spreads out over the lake ice and the pack grounds.) As the run passes the West Channel split it can move into the east arm past the Fishing Village. If it moves far enough into the east arm it can cause a rapid and substantial increase in water level at the Fishing Village. The observations and historical data suggest this is not the norm however, with a jam forming at the mouth of the east arm of the West Channel only approximately 20% of the time.

Figure 6.34 shows the normal location of the toes of the jam after initial break-up in the town. Although water levels may be quite high at this time, discharges are usually still relatively low and no serious flooding normally takes place.

The jam toes in the East and West Channels typically remain in place over the next few days. However the

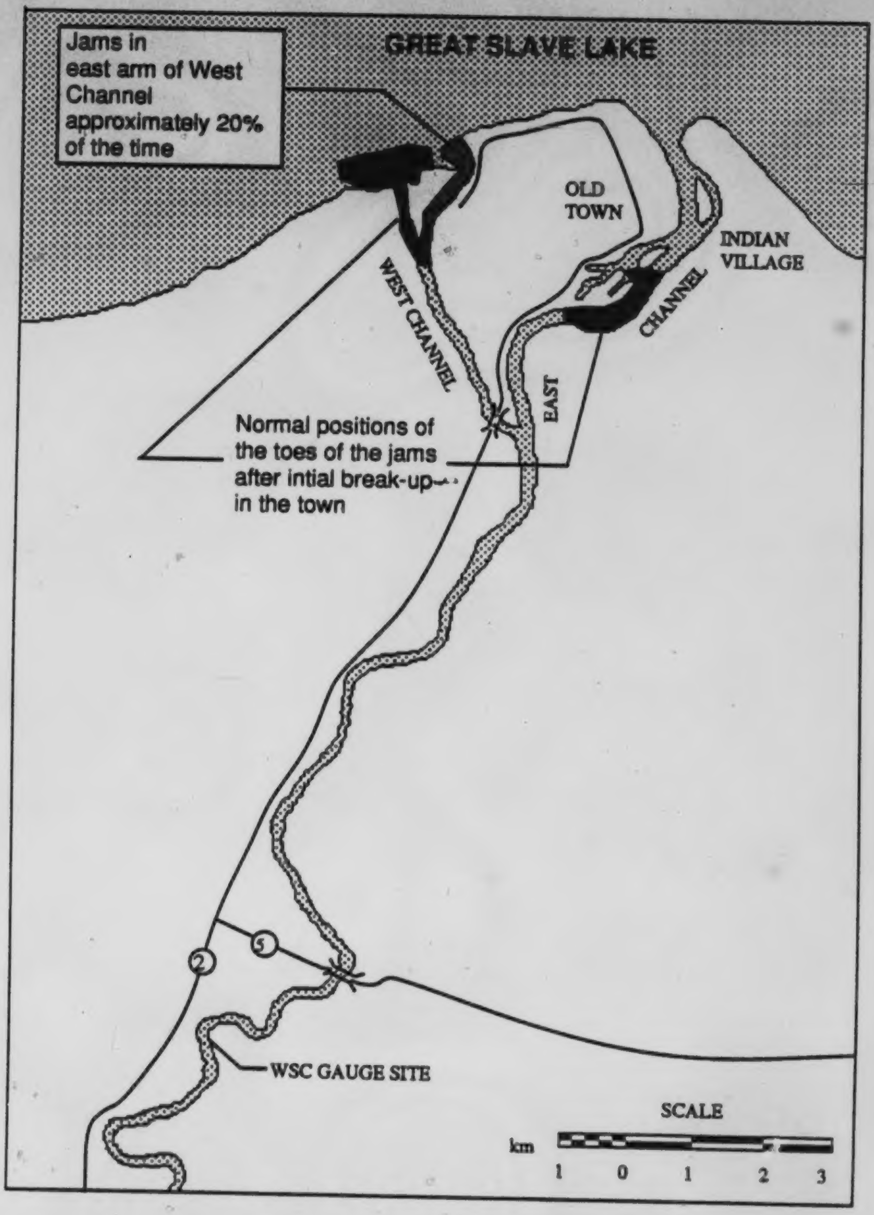

GREAT SLAVE LAKE
Jams in east arm of West Channel approximately 20% of the time
OLD TOWN
INDIAN VILLAGE
WEST CHANNEL
EAST CHANNEL
Normal positions of the toes of the jams after intial break-up in the town
2
5
WSC GAUGE SITE
SCALE
km
1 0 1 2 3

Figure 6.34 Typical locations of the toe of the jams after intial break-up in delta

discharge continues to increase if temperatures remain warm and break-up begins on the river above the falls.

Whether serious flooding occurs in the Town depends of the conditions and configuration of the jams in the town when the peak discharge arrives and the magnitude of the peak. The peak discharge at Hay River normally occurs 4-8 days after the original break-up in the town. After the original break-up up to 50 km of river can be open. With warm spring temperatures this water will warm and begin to melt the jam in the delta. If the peak discharge is high and arrives before significant melting of the jam has taken place, serious flooding in Hay River can be expected. Additional variables that can be involved in the flooding are surges released by ice jam failure upstream, and rainfall, both of which can increase the peak discharge.

In the East Channel the most severe flooding occurs when the peak discharge arrives and has enough force to dislodge the toe of the jam at Island C-D (km 1111) while the jam is still reasonably developed. The resulting ice run will then stall against the still competent lake ice at the mouth of the East Channel. This combination of circumstances only happens infrequently, with the only recorded instances being 1914 and 1963.

Typically the toe of the jam will remain at Island C-D if the ice is still competent. For example, in 1985 the discharge was equal to about the 100 year discharge yet the toe remained at Island C-D. It seems this toe will not normally move until the head of the pack has progressed downstream enough (by melting from warm water) that warm water reaches the toe of the jam and begins to deteriorate it. Once the toe has deteriorated enough the jam will move downstream. At this point the jam is normally quite short. Despite this the jam at this stage is still a threat when it moves to the mouth. The characteristic sharp increase in water level across the toe region of the jam can be sufficient to flood the low lying land near the mouth if the discharge is high enough. This process will produce flood stages in the East Channel but not near the stages that occur when the jam moves down suddenly when still fully-developed and accompanied by a "high discharge".

In the West Channel the most significant flooding occurs when high discharge occurs after a jam has formed on the east arm of the West Channel. This occurred in 1985.

In many years, the jams, and the ice in front of the toes of the jams, are sufficiently deteriorated by the time the peak discharge arrives that they simply washout into the lake.

6.5 Discussion of Ice Regime

Field studies are an essential part of any ice jam flood analysis. Ice processes are not well enough understood that an assessment of break-up processes can be made from a physical description of the site. Break-ups must be monitored by the study personnel at least once if any understanding of the break-up process is to be developed. Historical data can be very useful, but in retrospect much of the data for historical sources would have been of little value without the perspective gained from the field work.

Although no serious flooding took place in these years, conditions were such that many of the features evident in extreme flood years were present, only on a lesser scale. The field work provided much insite into the ice regime at Hay River.

With the understanding of many of the ice jam processes and the ice jam profiles obtained from the field work it was possible to calibrate a computer model to predict water levels in the delta. The calibration of this model is presented in the following chapter.

7. Ice Jam Profile Model

7.1 Introduction

In the deterministic approach, one of the major obstacles is the calculation of the water surface profile produced by an ice jam. Much work has been done on the calculation of water surface profiles in open water situations, but because of the complexities involved, little in comparison has been done for the ice jam case. The calculation of the water surface profile of an ice jam was necessary to produce rating curves which were used in the forecasting procedure.

A typical profile of an ice jam was discussed briefly in Chapter 1. In mild channels the profile is a result of the change in roughness from the smooth downstream ice to the rougher fragmented ice, resulting in a gradually varied flow profile of the M2 type. This M2 curve extends through the 'downstream transition' section of the jam. If the jam is long enough, in a relatively prismatic channel the jam will contain an equilibrium section.

An ice jam must sustain the downslope component of its own weight and the drag of the flow moving underneath. Therefore if the jam is to be stable it must be strong enough to transfer these loads to the obstruction downstream (the solid ice sheet) or, by shear, to the banks. In a break-up jam little or no cohesion exists between the ice fragments.

The jam must therefore rely only on inter-particle friction for its internal strength and some confining stress must be present, much like a granular soil. In a jam the confining stress is due to the opposing actions of the buoyancy of the submerged ice and the weight of the unsubmerged ice. To increase the confining stress and thereby, the internal strength, the jam must thicken. In a jam, the increase in thickness is the result of 'shoving'. At some section in the jam the load will became too large and cause this section to collapse, generating a new larger thickness that is sufficient to resist the applied force. This increase in thickness will also allow more load to be transferred to the banks, by shear.

The majority of work on ice jam water levels has followed from the early work of Pariset and Hausser (1961) and Pariset, Hausser and Gagnon (1966). This work was based on the analogy between ice blocks confined between banks of a river and a granular material confined between silo walls. The latter was formulated by Janssen (1895). Following closely the work of Pariset and others, more recent work (Uzuner and Kennnedy, 1976) has developed a more complete derivation of the equations governing ice jams. This work has lead to the development of the differential equation describing the variation of the thickness of the accumulation:

$$[7.1] \quad \frac{dt}{dx} = \frac{\rho' g S_w}{2K_p\gamma_e} + \frac{\tau_i}{2tK_p\gamma_e} - \frac{K_{xy}\tan\phi\, t}{B}$$

where t = thickness

ρ' = ice density

g = acceleration due to gravity

S_w = slope of phreatic surface

K_p = passive pressure coefficient

γ_e = $\frac{1}{2}\rho' g\left(1-\frac{\rho'}{\rho}\right)(1-e)$, a measure of the average confining stress at a section

τ_i = shear stress applied to jam underside by flow of water

K_{xy} = lateral stress transfer coefficient = σ_y/σ_x

ϕ = angle of shearing resistance

B = channel width

σ_y = thickness-average normal stress at bank

σ_x = thickness-average and width-average longitudinal stress

x, y = streamwise and transverse coordinates respectively.

Under uniform flow conditions $dt/dx = 0$ and $S_w = S_f = S$. Follcwing Beltaos (1984) substitution of these relation into Equation [7.1] and some algebra yields an expression for the equilibrium jam thickness:

[7.2] $$\frac{t_{eq}}{S\ B} = \frac{6.25}{\mu}\left(1 + \sqrt{1+0.35\mu\frac{R_i}{SB}}\right)$$

where:
t_{eq} = equilibrium accumulation thickness
μ = $K_{xy}\ K_p \tan\phi(1-e)$

The hydraulic radius of the ice influenced portion of the flow in a wide channel can be approximated as (Gerard and Andres, 1982):

[7.3] $$R_i = \frac{h}{1+\left(\frac{k_i}{k_b}\right)^{-p}}$$

where:
h = depth of flow under the jam
k_i= hydraulic roughness of jam underside
k_b= hydraulic roughness of the bed
p = coefficient based of power law expression for average velocity (1/4 for Manning equation equivalent)

With Equation [7.2], an approximate value of μ, and application of standard hydralics to find R, an estimate of the jam thickness in an equilibrium reach can be made. The water level can then be calculated from $d = h + (\rho'/\rho)t$.

Normally ice jam water levels are calculated assuming the jam at the section of interest is fully developed and has an equilibrium thickness (constant thickness and uniform flow). This assumption is deemed conservative as the equilibrium stage is the highest than can be attained by a jam. Although Equation [7.2] assumes the channel is prismatic it is often used to obtain jam related water profiles in natural channels. Such channels are seldom prismatic, so it is assumed that the equilibrium thickness is applicable at any cross-section and can be calculated from local channel geometry and flow conditions.

The need to assume equilbrium thickness can limit the validity of this method in certain instances. In many cases the channel may be too non-uniform to assume the thickness can fully adjust to the equilibrium thickness from cross-section to cross-section. In other cases it may not be valid to assume that equilibrium thickness has been reached at all, either because the jam is too short or the area of interest may be in the developing toe region of the jam.

The features of the Hay River delta are such that to use equilibrium assumption to calculate ice jam water level profiles would be questionable. The river morphology changes dramatically in the delta region making the channel very non-uniform. Also the jam tends to stall at the mouth of the river where much of the 'Old Town' is situated. It would be unrealistically conservative to assume the jam has reached equilibrium thickness at this location.

To obtain realistic results in the Hay River delta it was necessary to use a computer model which was capable of calculating the thickness and water surface profiles of an ice jam over its entire length in a non-uniform channel. A review of the literature found that three models exist which calculate a water surface profile over the entire length of the jam. It is known that other models have been developed by consulting firms, but these are not available for use or evaluation. Only the results of Uzuner and Kennedy (1974,1976), Beltaos and Wong (1986) and Flato and Gerard (1986) have been published. All three of these models make use of the differential thickness (Equation [7.1]) and varied flow equations. Both Uzuner and Kennedy (1974, 1976) and Beltaos and Wong (1986) use equilibrium conditions as a boundary condition from which the calculations proceed and therefore both presume the existence of an equilibrium section. By assuming the equilibrium condition exists these two models limit themselves for practical use. Unless the channel is prismatic, there is no possibility for an equilibrium section to develop and even in a prismatic channel, the accumulation length required for the jam to become fully-developed may not be achieved.

Flato and Gerard (1986) do not use equilibrium conditions as a boundary condition. This makes their model (ICEJAM ver. 1.5) much more flexible over a broad range of situations. Their scheme allows a complete water level profile of a jam to be calculated regardless of jam length or channel geometry. It was the only published model suitable for Hay River.

7.2 ICEJAM ver. 1.5

This is a numerical algorithm that iteratively solves the varied flow equations upstream, as is usually done in a mild channel, and then solves the differential thickness equation [7.1] downstream with the waterway depth profile just computed. This iterative cycle continues until convergence is attained. The main elements of the algorithm are shown in the flow chart of Figure 7.1.

The program starts by reading constant data like discharge, porosity, density, and jam strength parameters. Next, data for each cross-section is read, as well as ice and bed roughness. The solution begins by calculating the normal depth at each cross-section assuming an ice cover exists. Using this flow profile, a first estimate of the ice jam thickness profile is obtained. Using the thickness profile a new water surface profile is calculated. With the new water surface profile a new thickness profile can be calculated and so on until a specified tolerance is obtained.

The downstream boundary condition for the depth calculation is provided by the uniform flow depth under the solid ice sheet. However this downstream boundary condition required modification for use of the model in Hay River. Because the toe of the jam can form near the mouth of the river the depth of flow in the river at the toe is not the normal depth but that controlled by the lake level. The model was therefore altered such that the downstream boundary

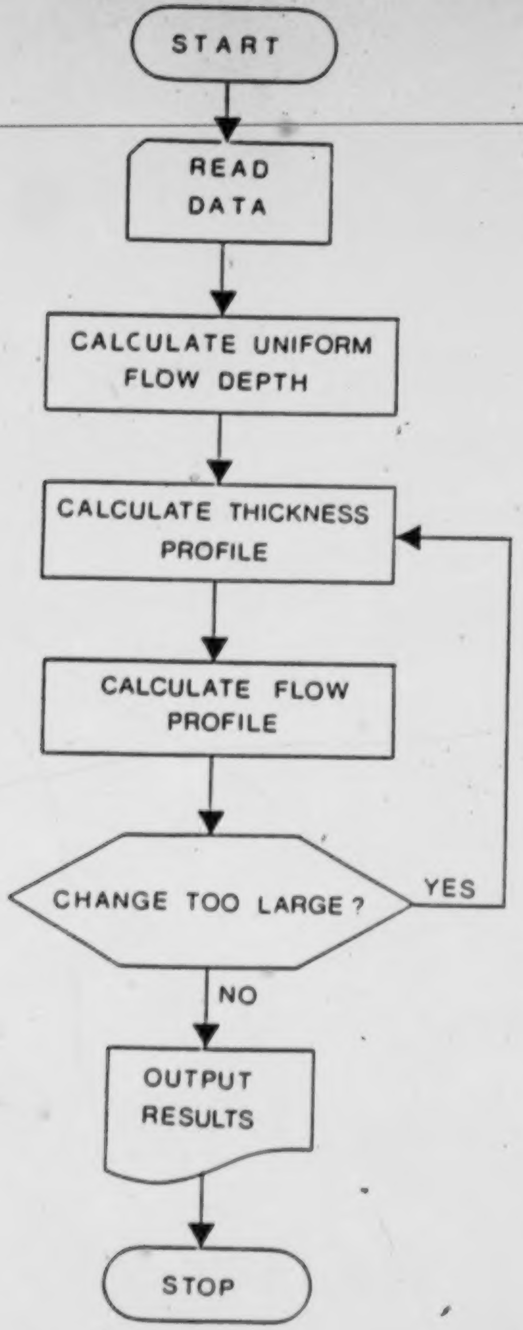

START
READ DATA
CALCULATE UNIFORM FLOW DEPTH
CALCULATE THICKNESS PROFILE
CALCULATE FLOW PROFILE
CHANGE TOO LARGE ?
YES
NO
OUTPUT RESULTS
STOP

Figure 7.1 Flow chart of ICEJAM program (modified from Flato and Gerard, 1986).

condition (depth of flow at the downstream end of the toe of the jam) could be arbitrarily set.

Another feature of this model is the 'floating toe'. During the thickness calculation the accumulation thickness is allowed to become as thick as necessary for 'geotechnical' stability. During the gradually varied flow sweep the average velocity in the waterway under the ice is calculated and checked against a specified erosion velocity for the accumulation. If the calculated velocity is greater than the erosion velocity, the accumulation thickness is reduced to simultaneously satisfy the gradually varied flow constraint and the erosion velocity constraint. "It is presumed that the reduction in accumulation strength caused by this reduction in accumulation thickness can be provided by the solid ice sheet (ie. the force applied directly to the upstream vertical face of the solid ice sheet, and the shear between the accumulation and the underside of the solid ice) (Flato and Gerard, 1986)." Based on this assumption the solid ice must extend up to the section where no reduction in accumulation thickness is required to satisfy the erosion constraint. It is further assumed that the eroded ice is carried downstream to deposit under the solid ice. This forms a hanging dam accumulation under which is a waterway constant area. The assumed sequence of development of an ice jam pack is shown in Figure 7.2.

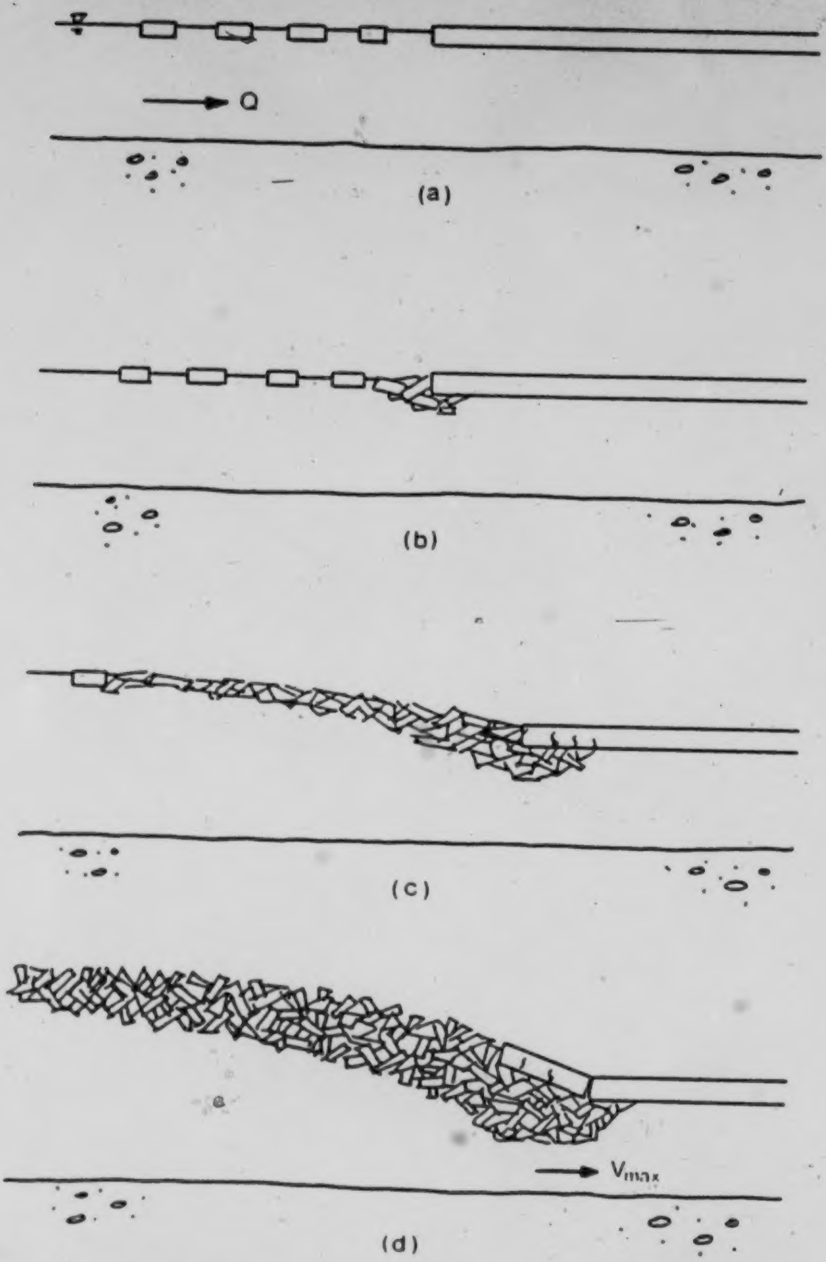


Figure 7.2 Development of jam toe (modified from Flato, 1986)

7.3 Calibration of the Model

The above model was calibrated using profiles obtained from the observations of break-up in 87 and 88. The model was only used for jams in the East Channel. In the West Channel ice fans out onto the lake ice and there is no defined toe of the jam.

The first obstacle in using the model was estimating the discharge in the East Channel. As mentioned quite reliable discharge estimates were available for the gauge at Hay River for both 1987 and 88. The problem was assessing the apportionment between the East and West Channels.

Because a fully-developed ice jam existed at the split in the cases for which the profiles were determined, standard hydraulic calculations and equilibrium ice jam thickness equations were used at the channel split to develop a relationship for flow down the West Channel, based on the elevation of water at the split. Discharge estimates were calculated for both the situation of a jam in the West Channel and open water in the West Channel. The resulting 'rating curves' are given in Figure 7.3.

Only one set of measurements of discharge down the West Channel could be found. These were done by WSC in 1985, and are shown in Figure 7.3. Two measurements were taken on different days but the measured discharge was the same. During these measurements the river was open at the split but

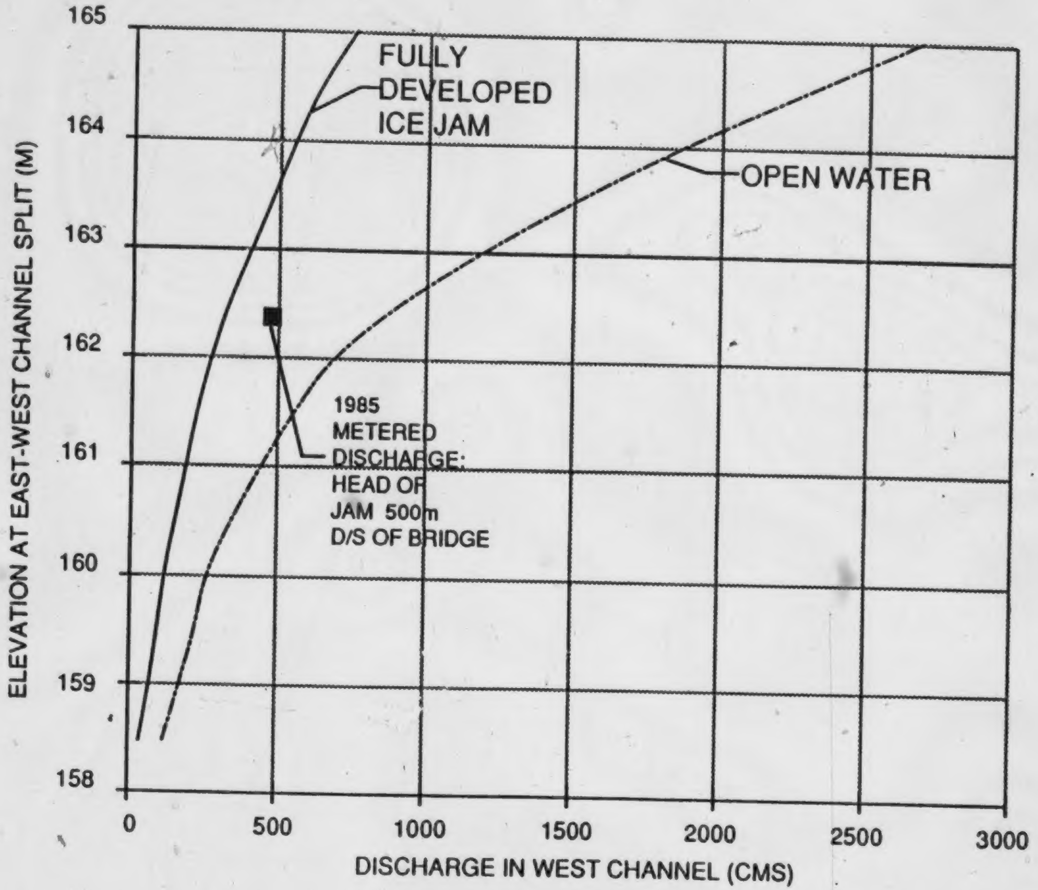


Figure 7.3 Discharge in the West Channel as a function of elevation at the West Channel bridge

the head of a jam was about 500 m downstream of the bridge. The measured value should therefore fall somewhere between the two curves because, although the channel was open the flow at the split would be influenced by the backwater of the downstream jam. As is evident in Figure 7.3 the measured discharge and water level elevation at the split indeed plots between the two curves.

From the discharge at the WSC gauge and Figure 7.3 the discharge in the East Channel can be calculated. In both 87 and 88 a fully developed jam was present in both channels at the split so discharges in the West Channel were simply read from the ice jam curve in Figure 7.3.

The roughness of the underside of the jam was used to calibrate water levels. It was found that an ice roughness of 1.1 m was needed to match the measured profiles. This ice roughness is reasonable as k_i (ice roughness) should be somewhere in the region of 1 to 3 times the average height of the ice projections on the underside of the jam (Rivard, 1985). Field observations noted that the projections on top of the jam were about 0.5 m in height (see Figure 6.16). Presumably the bottom of the is not unlike the top.

In calibrating the model it was also found that to obtain the location of the toe (the upstream of the solid ice cover) as measured in 87 and 88 an erosion velocity of 1.6 m/s was needed. This seems reasonable although there are no field or laboratory measurements to confirm or deny it.

The bed roughness used was 0.18 m and was obtained from open water profiles taken in the summer of 1987. All other parameter values used in the model are given in Table 7.1. The pack strength parameters used were such as to give the commonly used value of μ of 1.3.

As seen in Figures 7.4 and 7.5 the model results were very close to the measured values. It was found that the streamwise step size used in calculations in the toe region had to be quite small (50 m) to achieve stability.

With the model satisfactorily calibrated for two different discharges, ice jam rating curves were developed for the delta region. These rating curves could then be used in developing the flooding forecasting procedure.

7.5 Ice jam rating curves

A rating curve was developed for the East-West Channel split for discharges in the main channel upstream of the split from 200 to 1400 m^3/s. This was done for a jam with its toe at Island C-D, the normal occurrence, and the pack extending well past the split. The rating curve is given in Figure 7.6.

Serious flooding occurs when the toe of the jam sets up at the mouth of the East Channel. The model was therefore also applied to this situation and a rating curve developed for the East-West Channel split and for a point opposite

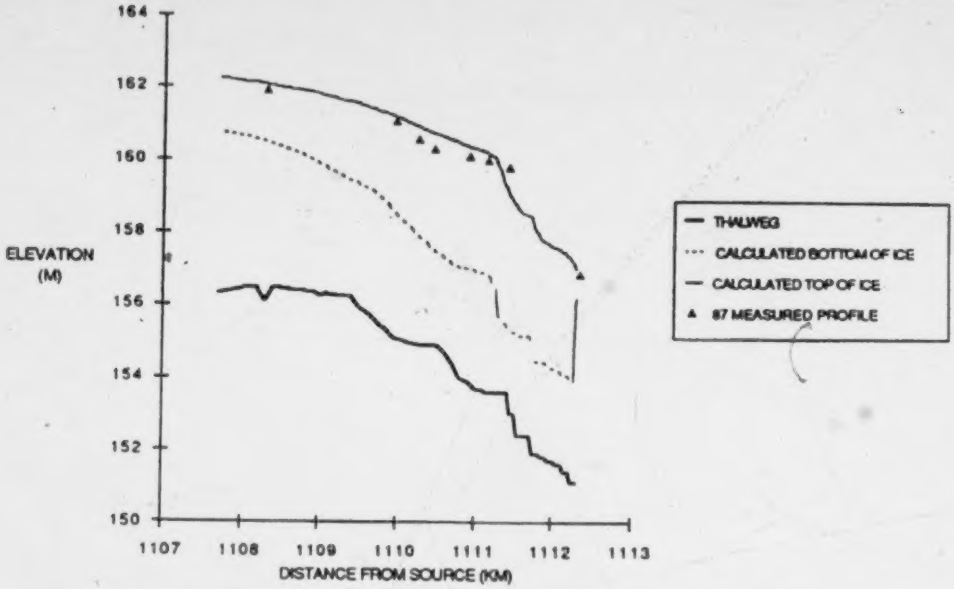


Figure 7.4 Model output in comparison to field data, 1987.

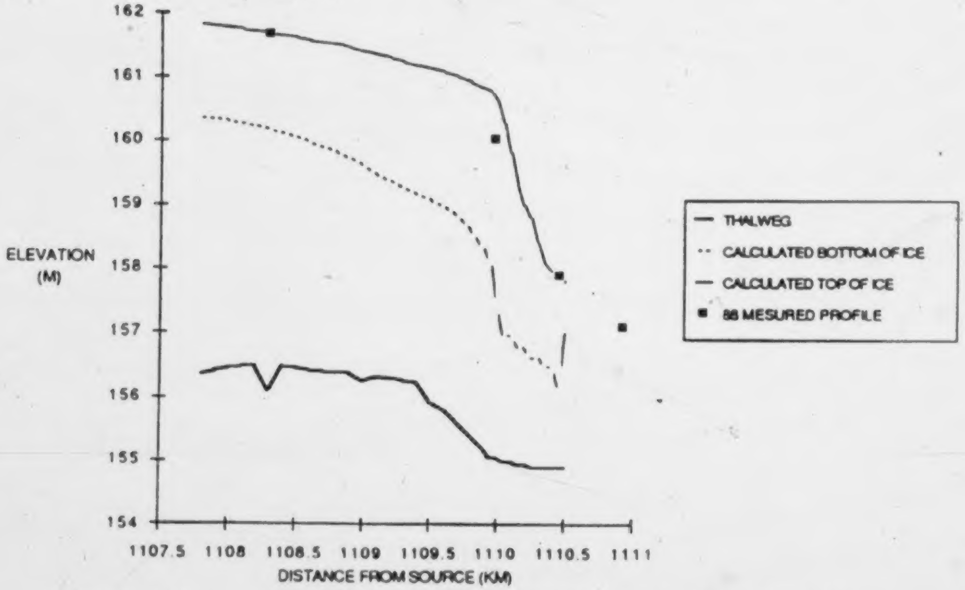


Figure 7.5 Model output in comparison to field data, 1988.

Table 7.1 Parameters used in ICEJAM model.

Intial thickness	1.50 m
Thickness at toe of jam	0.80 m
Tan (ϕ)	1.190
Ice density	920.0 Kg/m^3
Porosity	0.40
Shear coefficient	0.240
Passive pressure coefficient	7.55
Tolerance	0.01
Maximum velocity	1.6 m/s
Ice roughness	1.1 m
Bed roughness	0.18 m

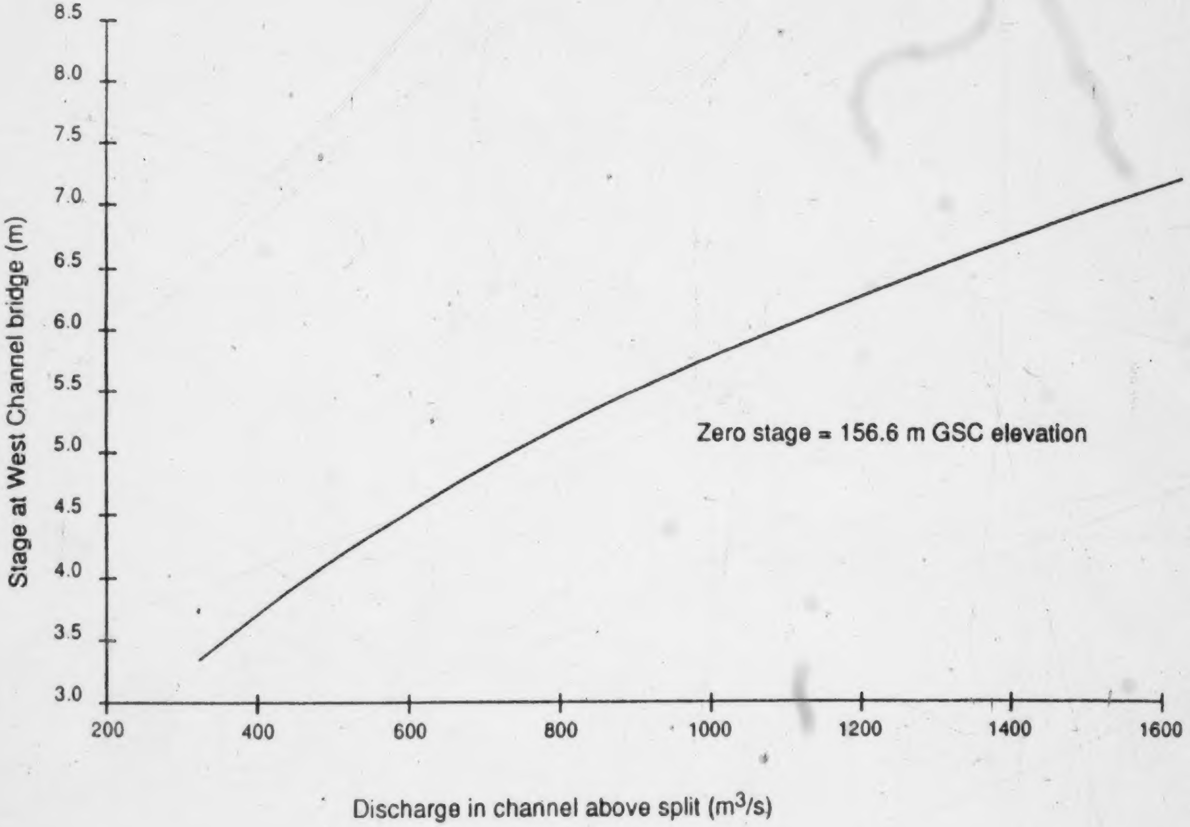


Figure 7.6 Rating curve for East-West Channel split for discharges at the WSC gauge.

Island A (km 1113). Figure 7.7 gives a typical calculated profile through such a jam for $Q = 1000\ m^3/s$. From the Figure it is evident that the pack thins just upstream of the toe. This is caused by the very large waterway area this region, which gives a mild slope.

It was found that the rating curve at the split was the same as the one developed for the toe at Island C-D. Obviously the East-West Channel split must be in or near the fully developed portion of the jam when the toe is at Island C-D.

The rating curve for the East Channel at Island A is given in Figure 7.8. Water levels for the 1963 flood, when the toe was at the mouth, are known. Although no discharge measurements are available UMA (1979) estimated that the discharge was 900 m^3/s in the East Channel during this event. This estimated peak discharge and the corresponding flood level are very close to the rating curve.

An interesting feature occurred when the model was applied to a jam with its toe set between Island C-D and the mouth of the East Channel. No matter what location was tried it was found that the toe was unstable in this region. It was only at either the mouth or Island C-D that both the 'geotechnical' stability and erosion velocity criteria could be met. Therefore only jams with the toe at the mouth or at Island C-D were compatible with the model, and indeed, no

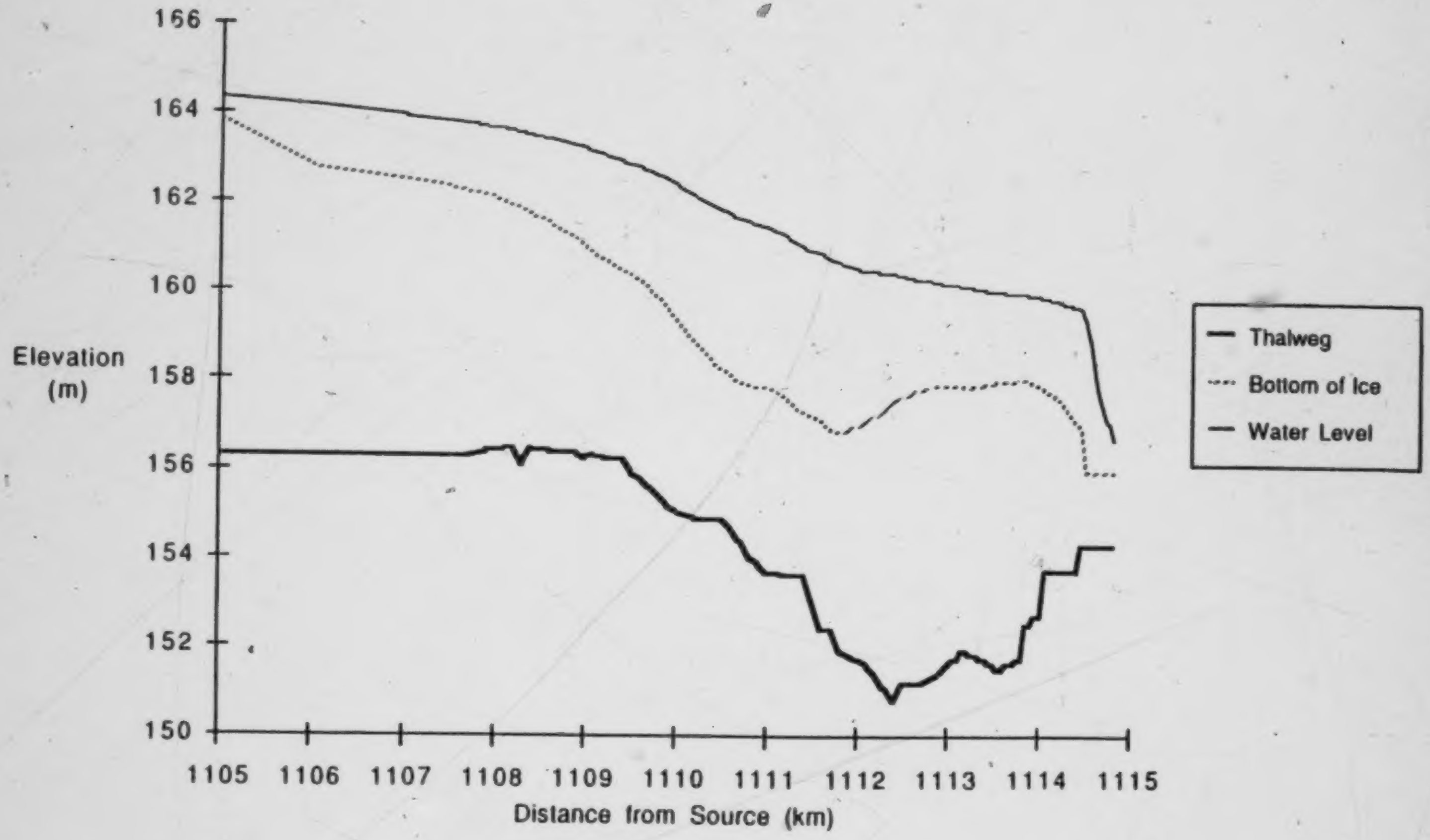


Figure 7.7 Model output for toe at the mouth, Q=1000 m^3/s.

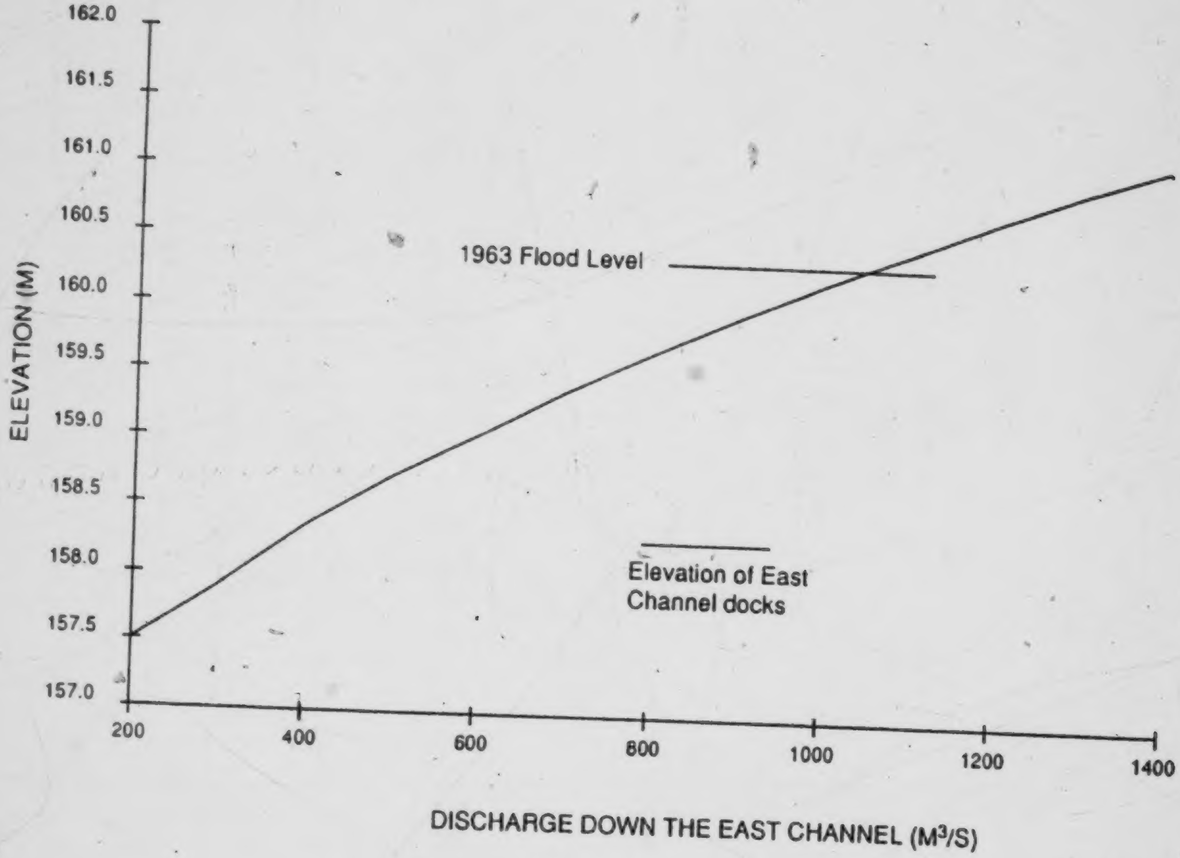


Figure 7.8 Rating curve for the upstream end of Island A, East Channel, for discharge in the East Channel

instances of a jam forming with its toe between Island C-D and the mouth could be found in the available historical data.

As mentioned earlier, ice in the West Channel tends to flow out onto the lake. There is therefore no defined toe. However the water level profiles taken along the jam at this location in 1988 (given in Figure 6.33) indicated that under these circumstances there is a constant slope in the West Channel near the mouth. This suggests the jam in this area may be close to fully developed.

A rating curve was therefore developed for the West Channel just upstream of the split of the West Channel assuming the pack is fully-developed at this section. The result is shown in Figure 7.9. The analysis was calibrated using data from 1987 and 88. Above an elevation of 160 m two curves are shown in Figure 7.9. The top line is from the above analysis. However significant overbank flow around the jam can occur at this site once the stage is over 160 m. The amount of this overbank flow is difficult to estimate. The peak water level at this site in 1985 was about 160.9 m (Underhill, 1985). Form the description of the surge event in the historical records and the Water Survey measurement of a discharge of 480 m^3/s in the West Channel, it is estimated the peak discharge was between 600 and 670 m^3/s. This suggests an appropriate rating curve for this site that allows for overbank flow is that of the lower curve in Figure 7.9. Values for the West Channel are for the upstream end of the

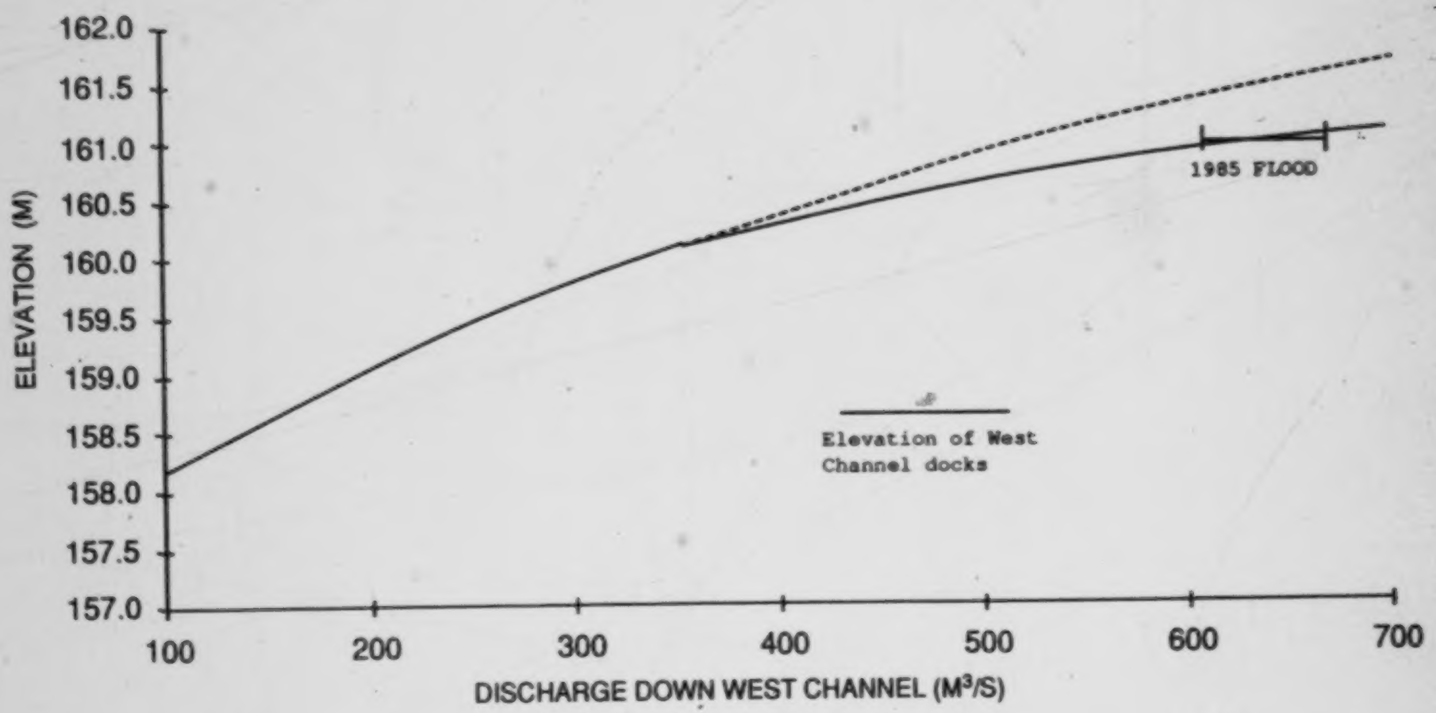


Figure 7.9 Elevation-discharge relation for West Channel Split for discharge down West Channel

Fishing Village (downstream end of airport). The field surveys of 1988 suggest this level can be transferred along the Fishing Village Channel assuming a water surface slope of about 0.9 m/km.

7.6 Discussion

The next task is to utilize these rating curves in developing an ice jam flood forecasting procedure for Hay River. This development is described in the next chapter.

8. Flood Forecasting Procedure for Hay River

8.1 Introduction

Ice jam flooding is characterized by a sudden and sometimes catastrophic increase in water levels. Because of the complexities involved in the break-up processes even experienced and knowledgeable personnel have difficulty determining if flooding is a possibility at any given time during the break-up. This was highlighted in Hay River in 1985. Town personnel monitoring break-up felt part way through the break-up that little chance existed of flooding occurring and monitoring of the river curtailed. Soon after this the most severe flooding ever experienced in the West Channel occurred. Because of the timing of the flooding (2:00 am) and the severity of the flooding, most residents agree that it was simply luck that there was no loss of life. It was this event that indicated the need for a systematic procedure to predict impending ice jam flooding at Hay River. Any advance knowledge of the severity of break-up can be used to implement defensive strategies.

Break-up is a complex process involving the interaction of physical features of the site, and meteorological and hydrological inputs. The physical features remain relatively constant year to year. The variability in the break-up process is primarily related to the meteorological and hydrological factors. Hence, for a given site it may be possible to develop a relationship between the variable hydrometeorological antecedents and the severity of break-up.

8.2 Past Studies

Much of the early work relating hydrometeorological antecedents to break-up processes seems to have been done in the Soviet Union. This work was documented by Shulyakovskii (1963). Shulyakovskii uses what he calls a "heat input" ΣE at the site to develop relationships for the severity and timing of break-up. The relationship between the required "heat input" at break-up and break-up parameters was in general assumed to be given as follows:

$$[5.1] \qquad \Sigma E = f(t_i, t_s, \Phi, v, Y_o, \Delta Y, \Sigma E_b)$$

where:
t_i = ice thickness
t_s = snow depth
Φ = parameter of stream morphology
v = flow velocity at break-up
Y_o = stage prior to break-up
ΔY = increase in stage at break-up
ΣE_b = heat input to the ice by warm water

He suggests, however, that not all of the above parameters would necessarily be involved at each site. He describes a number of prediction techniques developed from historical break-up information that involved various combinations of the above parameters.

For example, to predict break-up stages on the Tom River at the town of Tomsk, he reports an empirical equation involving 4 parameters. These were ice thickness, depth of snow on the ice, the ratio of heat input at the jam site to heat input in the basin that supplies discharge to the site, and the onset of negative air temperatures in the break-up period. These were all used to calculate his ΣE and predict severity of break-up. Similar relations were developed for other sites and other rivers. They were all empirically derived from historical data and normally contained 3 to 4 of the parameters.

Beltaos and Lane (1982) also developed a relation for stage during break-up for some Canadian rivers. The work followed closely that described by Shulyakovskii. In calculating ΣE for the site they used air temperature, hours of bright sunshine, wind speed and vapour pressure. The final result of this work was a relationship between ΣE and the stage increase above the maximum freeze-up stage (a measure of Δy). One of the limitations of this study was that no allowance was made for variability in the discharge at break-up.

White (1984) developed a model for peak stage during break-up for the Red Deer River at Red Deer, Alberta. Its development was based on the statistical analysis of 48 hydrometeorological factors. A number of multiple regression models were developed with the best version including parameters such as chinook wind in the upper reaches of the catchment. This approach was highly empirical and little attention was paid to the physics of river ice processes.

Gerard and Stanley (1986) investigated the relation between hydrometeorological antecedents and break-up severity on the Yukon River at Dawson, Yukon. They speculated that the main factors governing break-up severity at this site were discharge and ice competence. Accumulated degree days of thaw was used as a measure for ice strength. A relationship was then developed between degree days of thaw, discharge and expected water levels. This study was only preliminary in nature and was limited somewhat by the lack of meteorological data. No radiation or bright sunshine data, which is a much better parameter for ice strength, was available for the site. Even so the developed relationship has worked well in predicting break-up water levels at Dawson over the last two years (R. Janowitz, Indian and Northern Affairs Canada, Whitehorse, personal communication).

Doyle (1986) carried out a similar study that related discharge and bright sunshine to break-up severity for the Athabasca River, at Fort McMurray, Alberta. This study demonstrated the much better agreement found if bright sunshine data is available and used.

A number of other studies have been completed which relate synoptic meteorological patterns and break-up severity. These include McMullen (1961), Savchenkova (1972), Fogarasi (1985) and Doyle (1986). All had only limited success at doing this.

The review of the literature on forecasting ice jam floods revealed that past work has been almost totally empirical and site specific. In many cases the work is limited by the availability of hydrometeorological data, a common problem in cold regions. Therefore only a few factors effecting break-up can normally be considered. Consquently the relationships developed feature a great deal of scatter, but even so the warning of impending severe flooding can be extremely valuable.

Because of the more complex situation, a somewhat different approach was used to develop a flood forecasting algorithm for Hay River in this study. Based on the understanding of the break-up ice processes in the reach gathered from the field observations and the review of the historical record, a much larger deterministic component could be built into the forecast algorithm.

8.3 Development of an Ice Jam Flood Forecasting Algorithm for Hay River

8.3.1 Introduction

The procedure developed for the town of Hay River assumes a joint effort will be maintained between the Town and appropriate Government agencies such as Indian and Northern Affairs Canada, Water Survey of Canada, Atmospheric Environment Service and the GNWT Emergency Measures Organization. To make the procedure practical it presumes only currently available hydrometeorological facilities, regular aerial reconnaissance of spring ice conditions by experienced observers, and provision by the Town of flood watch personnel.

The fundamental parameter that drives break-up events in the delta is the discharge. The algorithm developed assumes real-time, one to two-day, forecasts of this parameter at Hay River will be available from WSC. This is felt obtainable from a newly developed WSC gauge at the Alberta-NWT border. Because of the geography of the catchment only 6 percent of the basin lies below this gauge station. Most of this area is low lying and covered with muskeg and adds little to the overall discharge of the river. Therefore discharge data from the border should be very representative of discharges that can be expected some two days later in the Town of Hay River.

In developing the algorithm information from all parts of the study has been utilized. This includes historical data, break-up observations and results from the computer model for ice jam profiles.

8.3.2 Timing of Break-up

The timing of break-up was looked at briefly in this study. Hydrometeorological antecedents were analyzed to investigate their relation to the first movement of ice in Hay River. It was found that the governing factor was a rapid increase in discharge, over a period of about a day, at the beginning of the break-up period. No relationship could be found that predicted the onset of break-up more than one day in advance. Any relationships developed with a longer lead time contained a great deal of scatter.

However, from the review of historical data and the break-up observations it became obvious that the onset of break-up is not of critical importance for flood forecasting at Hay River. At most other sites (eg. Dawson, Yukon) the onset of break-up is followed closely by the peak stage. Therefore any predictive technique at these sites must be able to predict the onset of break-up accurately. At Hay River, as explained earlier, break-up occurs first below the falls. It is not until 4 to 8 days latter that the peak discharge, which is usually responsible for the flooding, arrives. For example it is normal practice by the Town Flood Watch to mobilize only after the initial break-up occurs below the falls. It was evident that visual inspection of the river below the falls was the best method for determining the commencement of break-up.

8.3.3 Flood Forecasting Algorithm

An overview of the procedure developed to predict the maximum expected break-up stages is presented in the 'flow chart' given in Figure 8.1. The algorithm has been calibrated using as much data as could be procured, except for 1988. The events of that year were used to provide preliminary evaluation of the algorithm's utility.

The procedure centres around predicting water levels at the East-West Channel split. This site was chosen as water levels there are indicative of whether flooding occurs in the East or West Channels. If high water occurs at the split, flooding can be expected along one or other of the delta channels.

The simplest relationship for water levels at the split would be the rating curve developed for this location as described in Section 7.5. This is presented in Figure 8.2, along with the actual peak levels at the split and their corresponding mean daily discharges, for all years with data. It is evident that many of the points lie somewhat above the rating curve. This is likely due to the effect of surges that occur during the break-up period. These are caused by failure of ice jams upstream of the falls. The short lived, but important, discharge increase they cause is not represented by the mean daily discharge. This was substantiated in the break-up observations of 1987. The water levels from this year, which were used to calibrate the

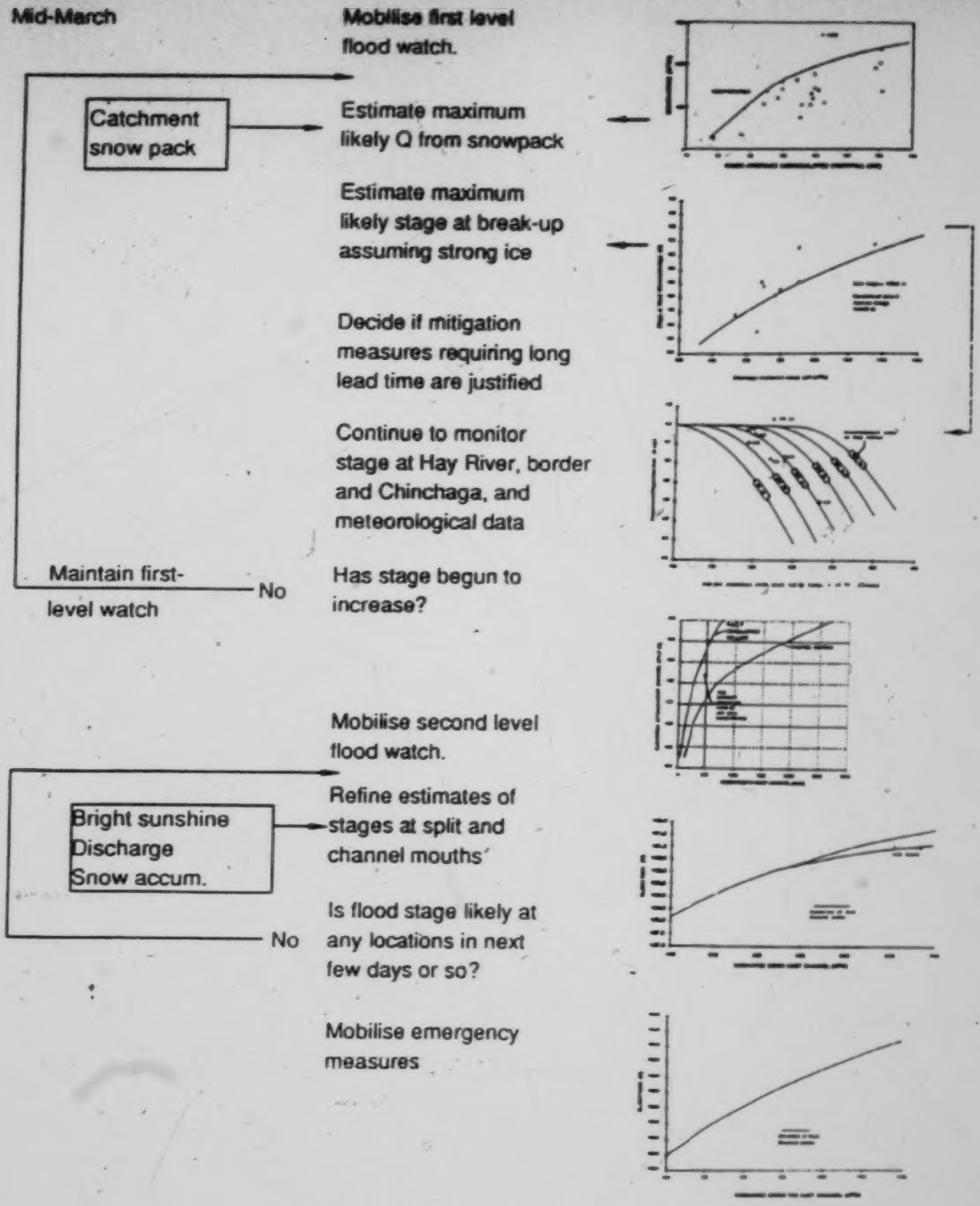

Mid-March
Mobilise first level flood watch.
Catchment snow pack
Estimate maximum likely Q from snowpack
Estimate maximum likely stage at break-up assuming strong ice
Decide if mitigation measures requiring long lead time are justified
Continue to monitor stage at Hay River, border and Chinchaga, and meteorological data
Maintain first-level watch
No
Has stage begun to increase?
Mobilise second level flood watch.
Bright sunshine
Discharge
Snow accum.
Refine estimates of stages at split and channel mouths
No
Is flood stage likely at any locations in next few days or so?
Mobilise emergency measures

Figure 8.1 Flow chart for flood forcast algorithm.

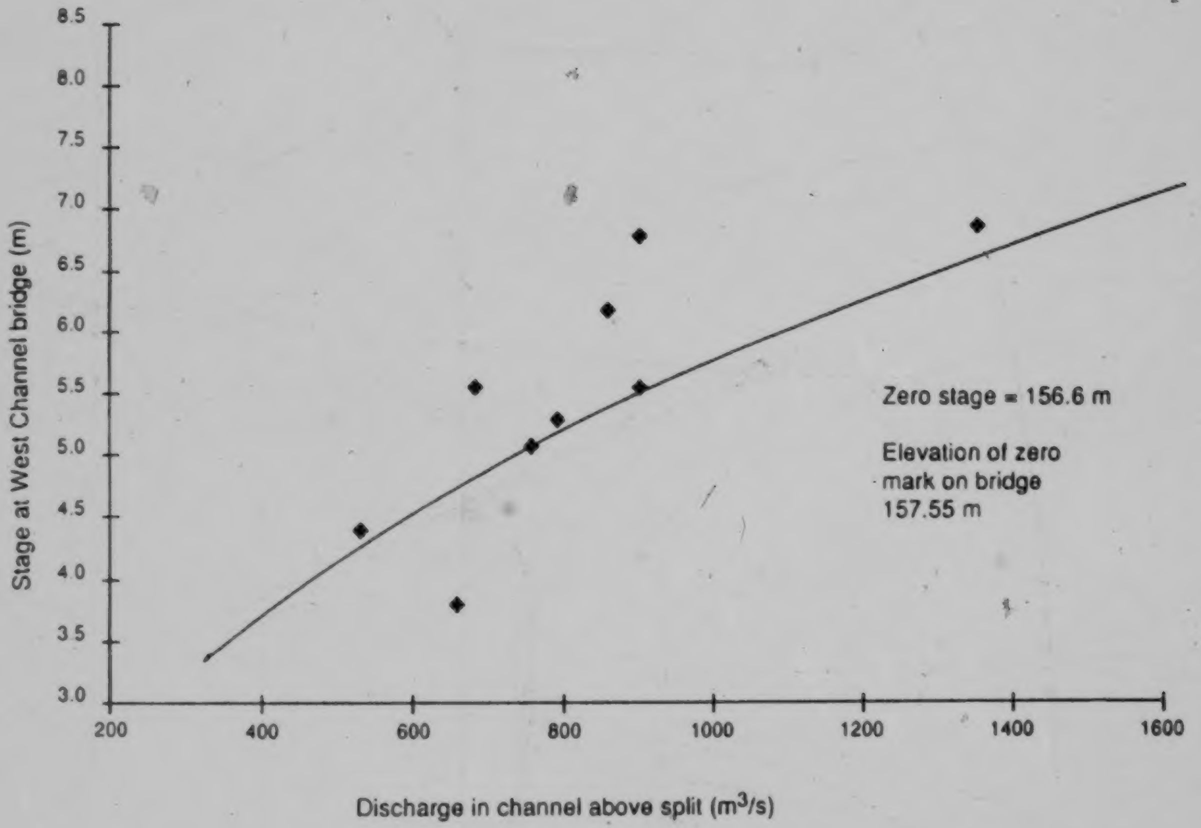


Figure 8.2 Stage to be expected at West Channel bridge as a function of WSC discharge at Hay River Station.

rating curves, were under steady conditions. If the surveyed high water mark and the corresponding mean daily discharge is plotted on the graph, the point is above the rating curve.

Using the rating curve with no allowance for the surges could give substantially lower values for the expected stage. Little data was available from WSC records to quantify these surges, so an empirical relationship was developed to try to quantify the surge effect.

As the surges are the result of the formation and subsequent failure of ice jams, the more conducive the situation is for the formation of jams, presumably the greater the chance that surges will occur. Almost all of the literature on ice jams agree that, for a given discharge, the more competent the ice the greater the chance for jam formation. The competence of ice is dependent upon a number of factors. These include freeze-up processes, winter regime, and energy input to the ice in the spring. As little information normally exists on the freeze-up processes they are usually ignored or assumed to remain relatively constant from year to year. The latter was assumed in this study. Although temperatures vary somewhat over the winter from year to year, ice growth is proportional to the square root of degree days of frost. In northern areas where values for degree days of frost are high, the difference in ice thicknes between a relatively mild winter and a severe winter are quite small. Therefore it was assumed that the ice thickness was similar from year to year.

The major remaining parameter effecting ice sheet strength is the energy input in the spring. This energy input is a result of solar radiation, air temperature and water temperature under the ice. Of these, solar radiation seems to have the greatest effect on ice strength (Bulatov (1972), Ashton (1985), Prowse, Demuth and Onclin (1988)). This radiation is absorbed within the ice sheet and, if this occurs at a higher rate than the resultant heat can be conducted away, the temperature will increase and eventually melt will occur. This This melt occurs first at the crystal boundaries, where the presence of impurities lowers the melting point, and will therefore occur for temperature below freezing. This selective melt causes a rapid reduction in strength. Bulatov (1972) reports that ice can lose almost all of its strength by candling while only losing 10 - 15 percent of its thickness. On the Peace River Andres found that melting of ice from radiation can occur when mean daily temperatures rise above -5 °C, Doyle 1986 also used this temperature for the commencement of melt.

Another factor effecting ice strength is the snow cover on the ice. Because of the high albedo of snow, even a thin cover will reflect most of the incoming solar radiation.

As snow depth on the ice and incoming radiation seem to have the most profound effect on ice strength, they were used for parameters to represent ice strength. As little snow depth data exists for Hay River, accumulated snowfall was used instead. No radiation measurements were available but bright sunshine data was available for nearby Fort Smith.

Bright sunshine was accumulated for mean daily temperatures above -5 °C up to the date of the peak level at the split for each year. As snow depth on the ice limits the radiation that can enter the ice, it was assumed that a suitable surrogate for actual energy input into the ice is given by:

$$E = S - a*Sn \qquad [8.1]$$

where S is the hours of bright sunshine accumulated at Ft. Smith after the mean daily temperature rises above -5 °C, Sn is the accumulated snowfall at Hay River and "a" is an empirical coefficient to be determined.

A relationship was then developed between snow depth, bright sunshine, and the increase in stage at the split caused by the surges (expressed as the ratio of the actual peak stages at the split to the rating curve stage) for all years with data. A table of the values used is given in Appendix D. The resulting empirical relation is presented in Figure 8.3. A second order polynomial $R = b+cE^2$ where R is the ratio of the stages and b and c are coefficients to be determined from the regression, was fit through the data. The assumed form of the relation is the simplest that would satisfy the requirement that there should be little influence of E for low values but that this should increase at higher E. The resulting formula for the relation is given by:

$$[8.2] \qquad R = 1.201 - 2.40*10^{-5}*E^2$$

Where E = S - 1.2Sn and is shown in Figure 8.3. The low value on the figure is from 1982 when one of the infrequent thermal break-up occurred. Therefore in this year no jam was formed in the delta and hence the less than one value.

A more explicit presentation is given in Figure 8.4 for $E \leq 0$. It is of interest that because of the snow on the ice the relation implies that the bright sunshine does not modify the stage until after about 100 hours of bright sunshine has accumulated . Indeed 1988 it was noticed that after about 125 hours of bright sunshine most of the snow on the ice had disappeared.

It can be seen from these figures that the largest error about 0.05. For the highest stage experienced at the split, which is 7.3 m, this would represent an error in predicted water level of about 0.4 m.

Using Figures 8.2 and 8.4 it is possible to predict water levels at the split if the discharge, accumulated bright sunshine and accumulated snowfall are known or can be forecast. A 2-3 day forecast is normally available for the meteorolgical variables. If values of discharge are obtained from the border station a 2 day forecast of mean daily discharge in Hay River is available. Hence Figures 8.2 and

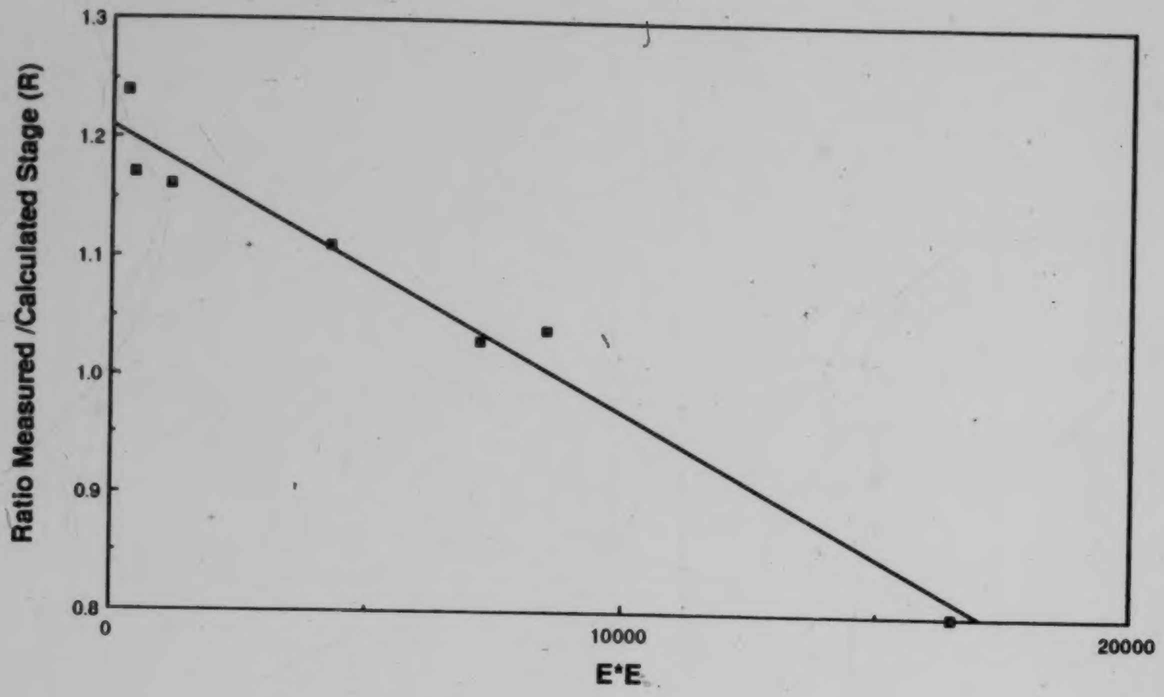


Figure 8.3 Regression for stage, bright sunshine, and snowfall data.

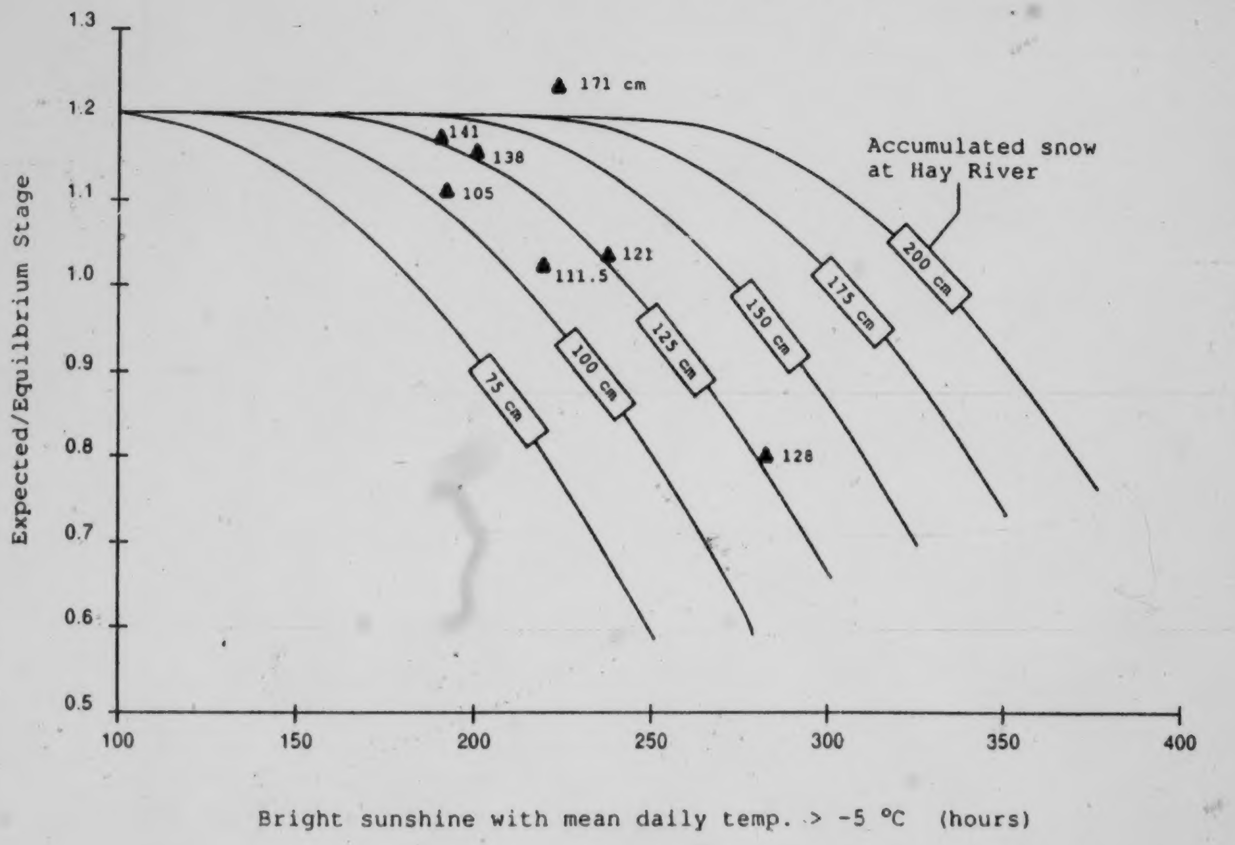


Figure 8.4 Multiplier factor for equilbrium stage at West Channel bridge as a function of bright sunshine and accumulated snowfall at Hay River

8.4 should allow at least a 2 day warning of possible high water at the split.

Flooding in Hay River is usually caused by one of two possible scenarios. Either a jam is formed in the Fishing Village branch of the West Channel (eg. 1985) or the jam that is nearly always present at Island C-D in the East Channel moves down early to the mouth of the East Channel. With a predicted water level at the split it is possible to estimate the likely high water levels that would occur at the mouths of the East and West Channel for each of these eventualities. The first step is to determine the discharge in each of the respective channels. This can be determined using Figure 7.3 and the forecast discharge in the main channel.

Levels for the mouths of the East and West Channels can be obtained using the rating curves developed in the preceeding Chapter. Using Figure 7.3 to estimate the discharge in the two Channels, Figure 7.9 estimates the stage in the West Channel. The estimated level from this figure cooresponds to the situation when a fully developed ice jam is at the West Channel split. Therefore this should be a 'worst case' level.

In the East Channel the level can be estimated for Island A using Figure 7.8. The level obtained from this curve should correspond to the "worst case" stage at the upstream end of Island A. The actual water levels may be somewhat less if the jam length has been shortened sufficiently when the jam moves down to the mouth.

From the above figures it should be possible to estimate expected peak stages for the East-West Channel split, and the mouths of the East and West Channels with about a 2 day warning. However, it would also be helpful for the town to have an indication of flooding potential early in the spring. This would give some lead time for initiation of any flood mitigation procedures judged worthwhile under the circumstances. What is needed for this is an early indication of the possible peak discharge. With this the above procedure could be used to give an indication of what flood levels could occur.

Discharge during break-up at Hay River is almost always the result of snowmelt. It should therefore be possible to estimate the maximum likely peak discharge during break-up from the snowpack depth in late March. As actual measurements of snowpack depth were only available for a few years, accumulated snowfall was used to represent the snowpack, as many more years of data was available for this parameter. To obtain a weighted average for the basin, data three long term meteorological stations - Hay River, High Level and Fort Nelson - were used. Using Thiessen polygons, the weighted average accumulated snowfall for the catchment is given by:

$$[8.3]\ \text{Accumulated snowfall} = \begin{aligned} &0.10 * \text{Snowfall Hay River} + \\ &0.34 * \text{Snowfall Fort Nelson} + \\ &0.56 * \text{Snowfall High Level} \end{aligned}$$

The values of this weighted snowfall and the related peak discharges are plotted in Figure 8.5 for years for which data was available. The upper envelope provides an indication of the possible maximum discharge. Although use of this discharge will indicate some flooding potential in most years, there have been several years when use of this approach would have indicated no risk of flooding unless substantial rainfall fell.

From Figure 8.5 it is evident that the data from 1985 was ignored in drawing the upper bound. This is because it is believed substantial rain fell during the spring break-up in that year. Although some rain was recorded at each of the meteorological stations during the 1985 break-up, it was not enough to explain the very high discharge. Wedel (1988) believes that a severe storm in the Cameron Hills area was responsible for the disparity. As no meteorological stations exist in the Cameron Hills, and the two WSC gauges on the streams draining these hills are not operative in spring, this was deduced from general weather patterns in the area. However discussion with various people involved indicated that this conclusion is somewhat contentious.

As this is an important consideration for the study, to investigate this further a simple water balance was done for that year. Over 20 years of hydrographs were analyzed for the WSC gauge at Hay River . From the analysis, recession constants, K, were calculated for each snowmelt peak using:

[8.4] $$Q_2 = Q_1 K^{-\Delta t}$$

where: Q_2 = instantaneous discharge rate at time t_2

Q_1 = instantaneous discharge rate at time t_1

K = recession constant, and

Δt = elapsed time interval (t_2-t_1)

These recession constants were remarkably consistent from year to year. The average for Δt = 1 day was K=1.044. It is then possible to integrate under the snowmelt hydrograph to obtain the total volume of water associated with the spring melt. The rising section of the hydrograph was ignored as it accounts for a very small percentage of the total volume of runoff. Integration of Equation [8.4] gives:

[8.5] $$S = \frac{Q_p}{\ln K}$$

where: S = total volume of water under the hydrograph

Q_p = peak discharge

K = recession constant

The measured peak discharge in 1985 was 1350 m^3/s. This with K = 1.044 gives a total runoff volume of about 2.7 km^3. The average snowpack on the ground just prior to break up was

10 cm of water equivalent (INAC, 1985). Assuming no losses in the system this represents a volume of 4.8 km^3 of water. This gives a loss cefficient of about 0.56 a value about 0.2 higher than any of the 21 other years analysed. This suggests the high discharge was likely caused by rain.

8.3.4 Overview of Flood Forecast Procedure

This section describes the recommended ice jam flood forecasting procedure in detail and outlines how it might be implemented. It follows the procedure shown in Figure 8.1. Details of the steps are as follows:

Step 1. Mobilize first level flood watch in mid-March and assess spring flood potential. This would just involve government officials and the head of the Town Flood Watch. At this time the reported snowfall accumulations for Hay River, Fort Nelson and High Level, can be used to calculate the weighted average accumulated snowfall for the catchment using equation 8.3. Then an estimate of the possible maximum peak discharge in the spring can be made from Figure 8.5. Using this discharge, the expected peak water level at the West Channel bridge can be estimated using Figure 8.2. From this it can be decided whether flood mitigation activities should be initiated. The first level flood watch should continue to monitor water levels at the

Chinchaga, border and Hay River WSC stations, and the precipitation in the catchment, and modify actions accordingly. When the mean daily air temperature at Hay River rises above -5 °C the above estimate can be refined using Figure 8.2 and 8.4, weather forecasts and the discharge at the border WSC station. At the first sign of significant water level increase at the WSC gauge at Hay River gauge the second-level flood watch should be mobilized.

Step 2. Once a persistent increase in water level at the Hay River gauge occurs, break-up can be expected anytime within the next few days (the actual time of break-up will be a function of developments in the ice cover upstream, both above and below the falls, but particularly the latter). The second level flood watch should then be mobilized. This will include all members of the Town Flood Watch. If significant flooding is anticipated, it might also include EMO personnel.

Frequent reconnaissance of the development of break-up and ice jams over a long reach upstream should now be undertaken, together with ground reconnaissance of developments below the falls, consideration of variations in discharge at the three WSC gauging stations, particularly the border station, and meteorological developments at the various meteorological stations in the catchment. From these various observations a continually updated estimate can be made of the peak discharge to be expected in Hay River a day or so ahead using Figures 8.2, 8.4, 7.8, and 7.9, and of the possible peak water levels at the West Channel bridge and mouth. If the East Channel jam moves to the mouth before significant melt has taken place and/or the discharge from upstream has decreased significantly, a flood stage may be possible near the mouth of the East Channel. The maximum likely water level to then be expected at Island A can be estimated from Figure 8.5.

As mentioned the error at the split can be in the order of 0.4 m. The split is the centre of the flood forecasting procedure therefore this error would be carried through the calculations for the estimated levels in the two channels. No doubt new errors will introduced in the calculation of the levels in the two channels, but palcing a value on these are difficult because of the lack of available data. In the East Channel predicted levels will be in many cases much higher than what is actually experienced because it is assumed that jam moves to the mouth of the channel. In the West Channel predicted values will also be high for many years as it is assumed that the jam in this channel is fully developed. In general the errors associated with the channel should be in the order of 0.5 m.

8.3.5 Application of the proposed algorithm to the 1988 break-up

The results of the 1988 break-up observations, were not used in development of the above algorithm. Instead they will be used to provide a preliminary evaluation of the algorithm's utility. This example is presented below.

In mid-March, 1988 the weighted accumulated snowfall for the catchment was 114 cm

From Figure 8.8:

Expected 'worst case' discharge = 950 m^3/s

From Figure 8.2:

At this discharge the likely water level = 162.25 m at the West Channel bridge, or a reading on the bridge pier of 15.5 ft (Town Flood Watch marks).

This is more than sufficient to cause concern. Any flood mitigation plans that require long lead time (e.g. snow clearing, snow bank construction...) should be initiated if considered worthwhile. Members of the first-level flood watch will begin to monitor water levels daily and obtain daily readings of precipitation, temperature and bright sunshine.

April 22 On this date a significant increase in water level was noted at the Hay River WSC gauge. Break-up should therefore occur within a few days if warm weather continues. The second-level flood watch should be mobilized. The first task is an initial aerial reconnaissance flight at least as far as the border to determine ice conditions.A ground reconnaissance to the falls should also be undertaken at this time to establish the situation at access sites. The ground reconnaissance should be repeated daily and aerial reconnaissance undertaken as often as conditions indicated.

April 24 On this date ground reconnaissance revealed that break-up had begun below the falls. An aerial reconnaissance at this stage would likely have been worthwhile.

April 26 Break-up appears imminent in the town.
An aerial reconnaissance would be undertaken as far upstream as appropriate.
At this time the discharge at the border station would likely have been about 700 m^3/s. (No actual values for discharge at the border were available in 1988 but they were possible to

estimate from measurements at Hay River at Hay River, allowing for travel time.) The accumulated bright sunshine at Fort Smith for mean daily temperatures > -5°C was 190.4 hr (forecasting two days in advance)
The accumulated snowfall at Hay River was 114 cm. There was no rainfall in the catchment. From Figures 8.2 and 8.4 the possible peak water level at the West Channel bridge in two days if break-up occurs would be 162.08 m. From Figure 7.3 the expected discharge down the West Channel under these conditions would be 280 m^3/s so that, from Figure 7.9, the expected water level at the West Channel split would be 159.6 m, or 1 m above the West Channel docks.
The expected discharge down the East Channel would be 700 - 280 = 420 m^3/s. Hence, from Figure 7.8, if the toe of the East Channel jam moved to the mouth, the expected water level at Island A would be 158.4 m, or 0.15 m above the East Channel docks without the influence of surges associated with jam formation at this site.

April 27 Break-up occurred in the town on this date. Ground reconnaissance should be undertaken in the delta to locate jam toes and water levels at salient locations to check with expectations. The reason for any disparity should be determined for consideration in future assessments as appropriate. An aerial reconnaissance should then be carried out as far upstream as required to check the state of the ice cover upstream of the falls. This would provide an indication if surges should be expected (are there any ice jams above the falls) The discharge at the border should continue to be monitored and the calculations of the previous day repeated.

and so on.

Following the above procedure, at about 18:00h on April 26th it would have been predicted that the highest levels for this spring would occur in about two days (ie. in the late afternoon of 28 April), and would be as follows:

At the East-West Channel Split: 161.75 m. The actual peak at this location was 161.68 m and occurred at 16:00 h on 28th April.

At the West Channel Split: 159.4 m. The actual peak was 159.3 m and occurred at 10:00 h on 27th April.

At Island A on the East Channel: 158.4 m. The actual peak of 156.7 m occurred at 12:00 h on 28th April.

8.4 Discussion

From the above example it seems the algorithm performs quite well. The expected high water at the West Channel bridge and at the Fishing Village predicted with about 2 day warning, were both within about 10 cm of the actual peak water levels. As indicated in the earlier discussion of the likely accuracy of the water level forecasts, such accuracy should not be expected every year. At Island A the peak water level was 1.7 m less than predicted because the initial jam at Island C-D more or less melted in place and did not move to the mouth.

In the example the discharge at the border was estimated from the discharge at Hay River allowing for an estimated travel time of 26 hours. They were used to highlight the fact that with discharge estimates from the border, a 2 day notice of high water is possible. It is presumed a rating curve for the border station will be available soon.

Although the above procedure seems to perform quite well, it has a number of limitations. The algorithm is based on the assumption that discharge estimates for Hay River will be available from the border station. However, during break-up discharge estimates are difficult to obtain because of the constantly changing ice conditions. To optimize the procedure a snowmelt-rainfall-runoff model for the Hay River catchment is desirable.

Another limitation is that the procedure is based on mean daily discharge, with only indirect account taken of surges through the use of Figure 8.4. It is apparent from Figure 8.2 that surges can account for an increase in water level of over a metre above that expected for the mean daily discharge. Furthermore, it is such surges that are responsible for the dramatic rates of water level increase (e.g. in 1985). If an estimate of the increase in discharge caused by a surge is available (from monitoring one of the upstream WSC gauges, for example) explicit account can be taken of the surge through the use of Figure 8.2 with the surge discharge. Alternatively, if the surge height is known (from a WSC gauge or from aerial reconnaissance), its effect can be estimated by simply adding it to the mean daily stage at the Split, and thereby to the levels expected for the two delta channels. Ultimately it would be useful to develop a unsteady flow model that would allow the routing of surges down through the delta, based on observed ice jams and their time of release, and ice conditions over the intervening reach.

After the initial break-up and setting of the jams in the delta, subsequent increases in water level depend on an increase in discharge. However, before this occurs, significant melt of the pack can take place due to an increase in water temperature. If the pack is reduced sufficiently before the peak discharge arrives the peak stage will be somewhat less. No account is taken of this in the above algorithm. This consideration is most important for the mouth of the East Channel. If there is a reasonable discharge and the East Channel jam still has a reasonable length when the toe moves to the vicinity of the mouth, flooding may occur. It seems that flooding in the East Channel is avoided most years because the toe remains near the Island CD site until the ice below the toe has weakened substantially. By this time the pack is short and the discharge has decreased. Indeed, it could be that the weakening of the ice cover is primarily due to the pack being held in place until it is short enough that the water moving under the jam from upstream has not cooled to zero before it moves under the downstream ice cover. It was noted in 1987 that the jam moved downstream not long after above-zero water temperatures were measured below the toe. It may therefore be possible to predict when the jam in the East Channel may move downstream by monitoring water temperature in the river. Investigation of these thermal aspects of the East Channel jam may allow further refinement of the above algorithm.

9. CONCLUSIONS AND RECOMMENDATIONS

9.1 Conclusions

This investigation has described the field documentation and presented an analysis of ice jam flooding at the Town of Hay River. The analysis has quantified the severity of the ice jam flooding problem in Hay River through a probability analysis and developed a flood forecasting procedure for the site. The complex morphology of the site dictated that special techniques in the analysis of ice jam floods were necessary. This included the need probability analyses to be done at three different sites to properly define flood water levels in the delta, the use of a model capable of calculating the thickness and water surface profile of an ice jam over its entire length in a non-uniform channel, and that the flood forecasting procedure contained a large deterministic component.

Historical data was used in the probability analysis. The analysis found that the 1985 event in the West Channel was below the 1% event and not an outlier. It was also found that the many man-made changes in the delta of the river seem to had little influence on flood levels.

An existing numerical model was used to synthesize complete ice jam water level profiles. Even with the complex morphology of the site the model was able to produce profiles very close to the measured data. It was found to obtain results close to the measured data in the toe region an erosion velocity of 1.6 m/s was needed. This model was used to produce an ice jam rating curve near the mouth of the East Channel for use in the flood forecasting procedure.

A flood forecasting procedure was developed for the Town of Hay River that gives at least a two day warning of high water. The procedure was applied to the 1988 break-up with considerable success. The procedure was limited somewhat from the availability of salient quantative data. Even with the this limitation the procedure should give 'good' estimates of possible peak water levels in any given year.

5.2 Recommendations for future work

The recommendations for further study are as follows:

1. Continued documentation of break-up processes on the Hay River. Areas that especially need further study are formation and subsequent breaking of ice jams above the falls, and melting of the jam in the delta region. Attention should also be paid to the processes that dictate whether flooding occurs along the East or West Channels.

2. The development of a snowmelt-rainfall-runoff model for the catchment. This would provide a longer lead time for the forecast procedure.

3. Development of an unsteady flow model that would allow the routing of surges through the delta.

4. The installation of radiation measurement instrumentation in Hay River. This would allow a much more rational procedure to be developed to estimate ice strength.

5. Further investigation of the thermal aspects of the East Channel jam to allow further refinement of the water level forecast for the East Channel.

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APPENDIX A

DIGITIZATION OF HAY RIVER

The Hay River was digitized from 1:50,000 NTS maps to provide an accurate reference of distances along the river. Physical features such as tributaries, settlements along the river, and where topographic contours crossed the river were noted during the digitization. All distances are from the source of the river, located at UTM 311280 / 6379670. Although it lies on the Chinchaga watershed this point was chosen as the source since it is the greatest distance from the mouth of the river. In total this distance from the source to Great Slave Lake is 1114.24 km

The digitizer used was an Intergraph Graphics Workstation, linked to a Digital Equipment Corporation VAX 11/730 with 400 megabytes of disk storage. UTM coordinates were used as the reference. Table A1 is a list of features digitized and their distance from the source.

TABLE A1
LOCATION OF PHYSICAL FEATURES FROM DIGITIZATION

Physical Feature	Distance from Source (km)
East - West Channel split	1107.40
Pine Point Bridge	1098.26
Louise Falls	1037.12
Alexandra Falls	1034.95
Grumbler Rapids	988.02
NWT-Alberta Border	945.17
Indian Cabins	920.63
James Creek	911.78
Steen River Settlement	888.48
Dizzy Creek	887.47
Steen River	880.72
Little Rapids Creek	862.19
Lutose Creek	855.24
Roe River	828.52
Slavey Creek	824.96
Melvin River	822.84
Meander River Bridge Crossing	814.73
Adair Creek	803.84
Meander river	799.10
Henderson Creek	781.07
Negus Creek	716.33
Hay and Chinchaga River Confluence	709.33
Highway 58 Bridge Crossing	612.48
Faria Creek	514.68
Haro River	426.96
Waniandy Creek	363.78
Tanghe Creek	102.65
Lennard Creek	96.41

APPENDIX B

RELIABILITY OF GEODETIC BENCHMARKS IN HAY RIVER

As in many northern areas the reliability of geodetic benchmarks must be considered. Because of soil conditions in the north, mainly permafrost, movement in benchmarks can occur regularly. To have a consistent datum for survey work bench marks were chosen which were considered reliable. These bench marks were chosen on the basis of a 1983 report by Underhill and Underhill, "Establishment of Bench Marks, Hay River, NWT", and conversations with the staff in Hay River.

In total five bench marks were chosen and all survey work was tied into at least two of these bench marks. A description and elevation for each of these bench marks, taken from Geodetic Survey of Canada, Vertical Control Data, Quad. No. 60115, February, 1985 revision is as follows.

82T109..170.024 m
Lat. 60-47.2   Long. 115-49.3
Northwest Land Forest Service, tablet in north concrete foundation of kitchen quarters, about 100 m southeast of highway, 67 cm from east edge, 36 cm below wood siding.

67T019..167.728 m
Lat. 60-48.6   Long. 115-47.3
Post office, Hay River, tablet in west concrete foundation, 1.8 m from southwest corner, 24 cm below siding.

67T022..168.017 m
Lat. 60-49.4 Long. 115-46.7
Steel truss bridge over West Channel, 2.5 km north of post office, tablet in top of north end of curve at northwest corner of bridge, 78 cm south of north end of steel railing, 21 cm east of west edge, 18 cm above deck level.

82T114..159.369 m
Lat. 60-51.6 Long. 115-44.2
N.T.C.L. Marine Maintence Building and Syncrolift, 1.6 km north of Hay River Hotel, tablet in north concrete foundation, 108 m from east corner, 1.30 m below aluminium siding.

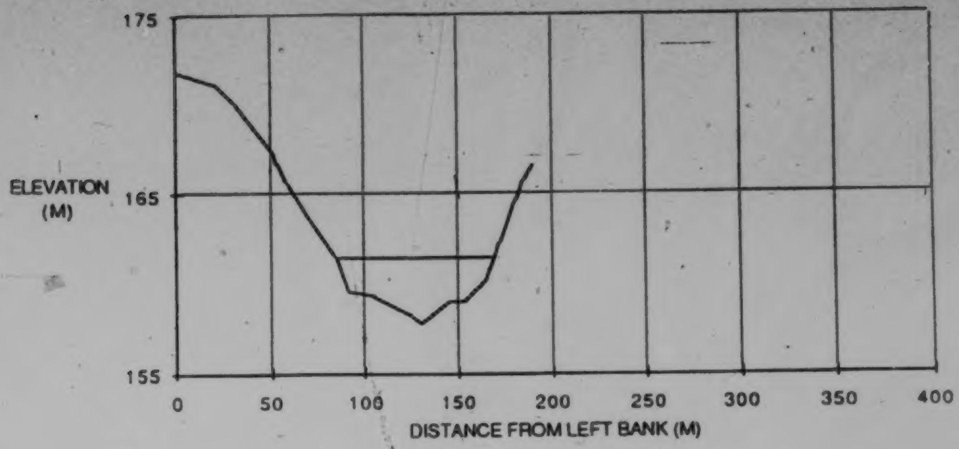
82T043..197.376 m
Lat. 60-40.5 Long. 115-58.3
Deep bench mark in manhole along Highway No. 2, 14.1 km southwest of junction with Highway No. 5, 122 m northeast of centre line of road to saw mill Patterson Enterprise, 23.0 m southeast of centre line of highway, 5.0 m south of power pole No. 26, 1 m below highway level.

This was used to tie in TBM used in spring at Patterson saw mill. A nail in poplar tree left bank, 8 m north of road. Elevation 170.737 m.

APPENDIX C

CROSS SECTIONS OF HAY RIVER

All cross sections were surveyed in the summer of 1987 are contained in this appendix. Included with each cross section are a description of the site and a table of surveyed points used to construct the cross section. The site description contains a visual estimate of bed material size, composition of banks (vegetation, etc.), location and elevation of temporary bench mark used, and any other observations made during the survey. All cross sections are referenced by distance from the source.



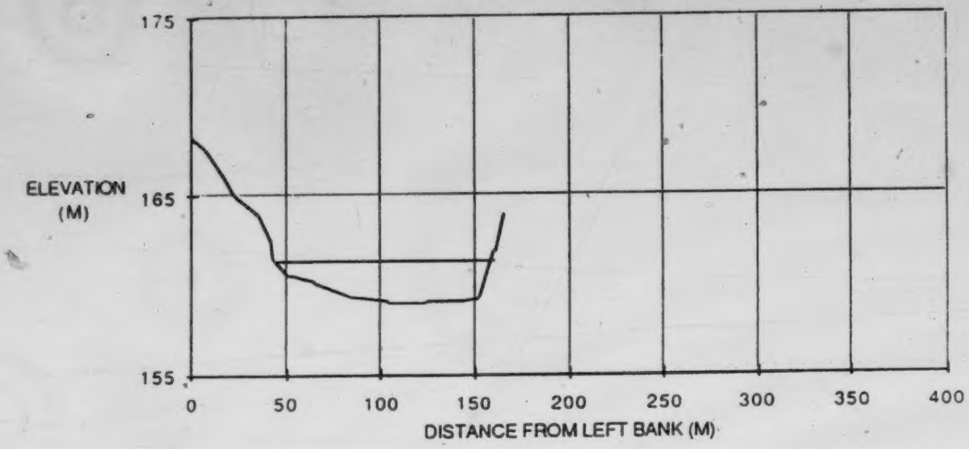
DISTANCE FROM LEFT BANK (M)	ELEVATION (M)
0	171.9
20	171.2
30.5	170.12
51	167.29
53	166.71
58.3	165.65
69	163.9
84.5	161.5
91	159.54
105	159.24
125	158.13
130	157.78
145	158.94
153	159.04
165	160.36
169.5	161.5
172.5	162.39
179	164.34
182.6	164.91
185	165.8
190	166.69

CROSS SECTION KM 1094.43

DESCRIPTION: This cross section is 1.1 km U/S of the Water Survey gauge site. The left bank is covered by poplar up to 51 m, after which the cover is willows to the water level. The right bank is grassed from the water level to 185 m, beyond which the trees start. The bed material had a D_{50} of 130 mm. Water level on the day of survey, July 18, 1987, was 161.50 m.

TBM: Spike in tree, top of left bank, 0.0 m on the cross section. Elevation 172.50 m.

Figure C.1. Cross section km 1094.43



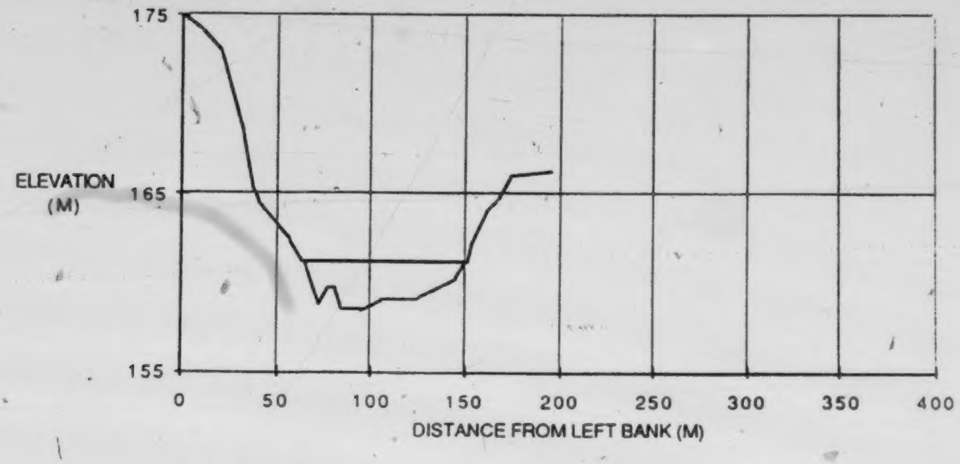
DISTANCE FROM LEFT BANK (M)	ELEVATION (M)
0	168.25
7	167.63
17	166.01
23	164.92
35	163.89
42	162.41
44	161.33
51	160.52
64	160.11
84	159.29
104	158.99
124	159.09
144	159.1
152	159.3
160	161.96
160.5	161.96
165	164.08

CROSS SECTION KM 1095.12

DESCRIPTION: This cross section is just U/S from the WSC gauge site. The left bank is treed to 23 m and from there willows extend to 37 m, with grass beyond to the water level. The right bank is grassed from the water level to 167 m, beyond which it is treed. The bed material has a D_{50} of 130 mm and the water level on the day of survey, July 18, 1987, was 161.33 m.

TBM: Spike in tree top of left bank, at 5 m on the cross section. Elevation 168.588 m.

Figure C.2. Cross section km 1095.12



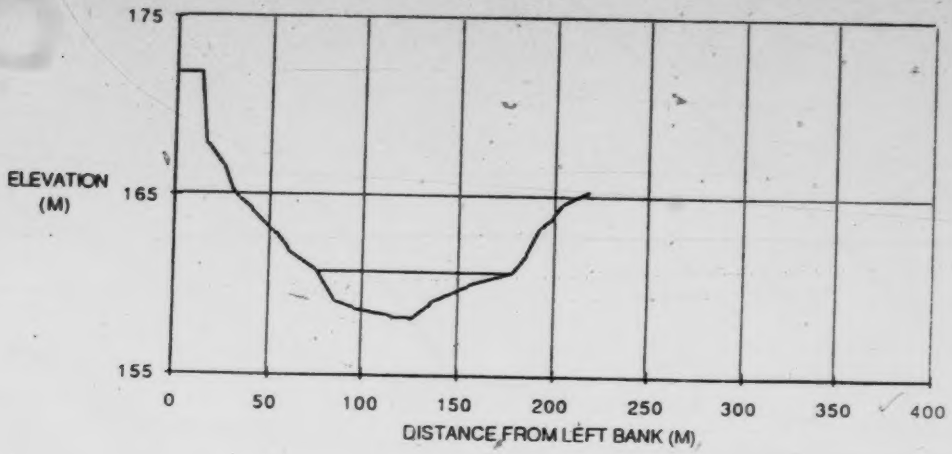
DISTANCE FROM LEFT BANK (M)	ELEVATION (M)
0	175
10	174.14
20	172.96
32	168.41
38	165.19
40.5	164.45
57	162.38
64.2	161.22
72	158.78
78	159.79
80	159.8
84	158.58
94	158.47
105	159.08
125	159.19
145	160.3
150.8	161.22
153	162.27
161	164.04
167	164.71
174	166.01
196	166.25

CROSS SECTION KM 1095.95

DESCRIPTION: This cross section is 450 m D/S of the Water Survey gauge. The left bank is treed to 33 m after which it is gravel to the water level. The right bank is grassed from the water level to 160 m, at which point the trees begin. The bed material has a D_{50} of 125 mm with some stones having a diameter up to 400 mm. Water level on the day of survey, July 18, 1987, was 161.22 m.

TBM: Spike in tree on the left bank at 35 m on cross section. Elevation - 168.564 m.

Figure C.3. Cross section km 1095.95



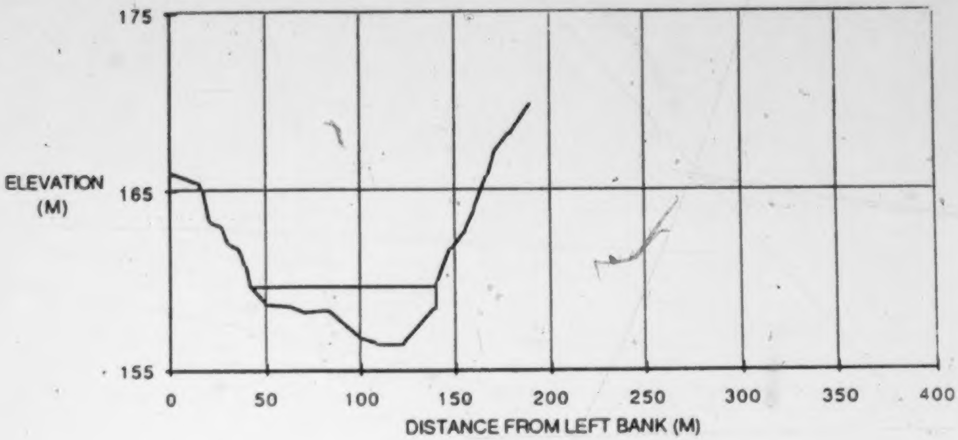
DISTANCE FROM LEFT BANK (M)	ELEVATION (M)
0	171.83
13	171.86
17	167.81
25.5	166.61
30	165.33
34	164.78
41	164.18
53	162.9
60	161.95
75	160.84
85	159.06
95	158.66
115	158.25
124	158.15
135	159.06
145	159.57
155	160.07
178	160.84
186	161.935
193	163.38
200	164.03
205	164.7
218	165.4

CROSS SECTION KM 1096.47

DESCRIPTION: This cross section is 1 km D/S of the Water Survey gauge. The left bank is covered with poplar up to 35 m. From 35 m to the water level the bank is gravel with no vegetation. The right bank consists of a gravel surface from the water to 190 m where willows start, with the trees starting at 200 m. The bed material had a D_{50} of 125 - 175 mm. The water level on the day of survey, July 18, 1987, 160.84.

TBM: Hub in ground on left bank at 60 m on cross section. Elevation - 162.006 m.

Figure C.4. Cross section km 1096.47



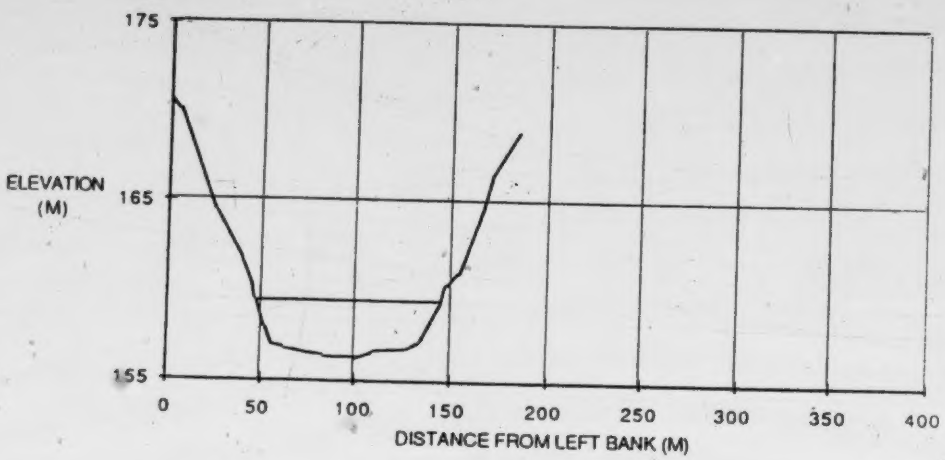
DISTANCE FROM LEFT BANK (M)	ELEVATION (M)
0	166.091
15	165.46
17	165.09
21	163.3
26.5	162.97
30.4	162.07
35	161.739
37.6	161.2
39	160.62
41.5	159.69
49	158.68
62	158.57
70	158.17
82	158.37
100	156.74
108	156.44
122	156.54
139	158.47
139.2	159.69
140	160
147.5	161.64
155	162.94
160	164.056
167	165.96
171	167.12
179	168.23
188	169.96

CROSS SECTION KM 1098.46

DESCRIPTION: This cross section is located 200 m D/S of Pine Point bridge. The left bank is treed with poplar from 0.0 m to 15 m; from there to 30 m the bank is covered with willows after which it is grassed to the water level. The right bank is grassed from the water level to 150 m where small poplars begin and at 180 m large spruce start. The bed material had a D_{50} of 100 mm to 120 mm. On the day of survey, July 18 ,1987, the water level was 159.69 m.

TBM: Spike in tree, top of left bank, directly D/S of Pine Point bridge, 180 m U/S of cross section. Elevation - 167.980 m.

Figure C.5. Cross section km 1098.46



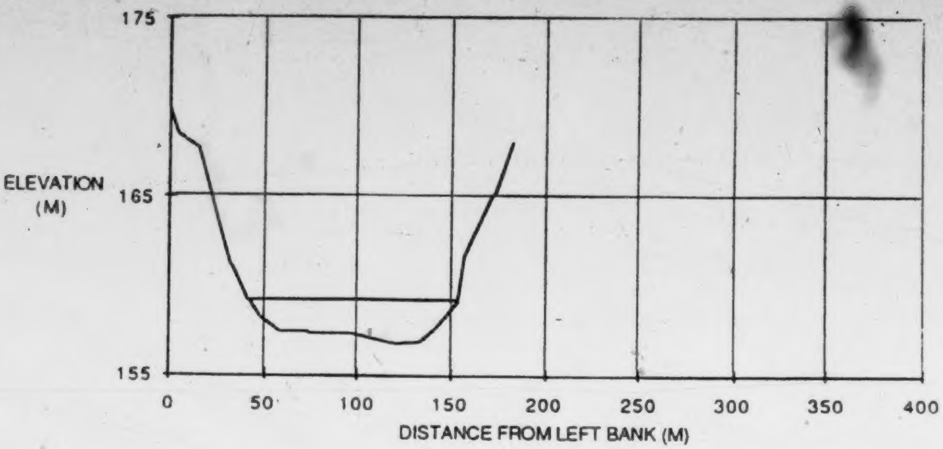
DISTANCE FROM LEFT BANK (M)	ELEVATION (M)
0	170.7
5	170.1
25	164.4
39	161.71
45	160.29
47	159.41
52	157.9
56	156.93
62	156.71
74	156.48
83	156.3
100	156.19
109	156.63
127	156.78
134	157.2
145	159.41
148	160.31
154	161
166	164.65
171	166.51
186	169

CROSS SECTION KM 1100.23

DESCRIPTION: This cross section is 2 km D/S of the Pine Point Bridge. The left bank is treed to 5 m from which point the bank is covered by tall grass until 25 m. Beyond this little vegetation exists on the bank to the water level. The right bank has little vegetation from the water level to 154 m where grass begins. Tree growth starts at 170 m. The bed material has a D_{50} of 100 mm and the water level on the day of survey, July 10, 1987, was 159.41 m.

TBM: Hub in ground on left bank at 23 m on cross section. Elevation - 164.984 m.

Figure C.6. Cross section km 1100.23



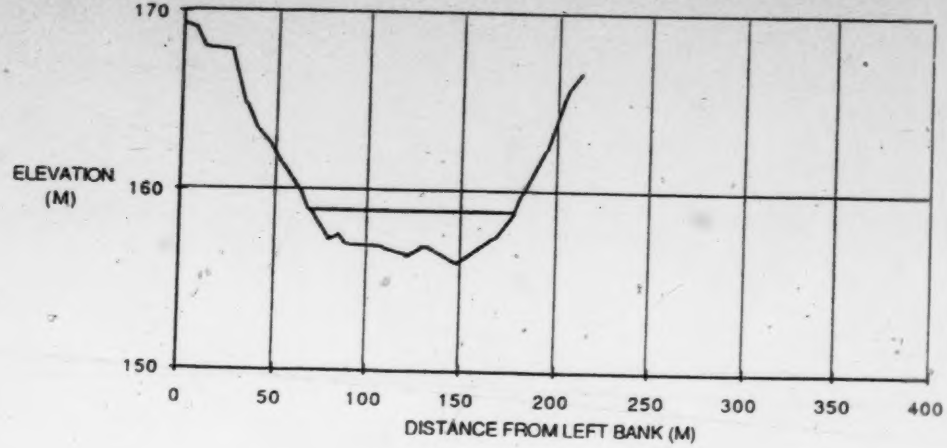
DISTANCE FROM LEFT BANK (M)	ELEVATION (M)
0	170
4.5	168.5
8	168.2
15	167.7
33	161.1
41	159.2
42	159.16
48	158.2
58	157.4
74	157.3
96	157.3
120	156.7
133	156.9
141	157.6
153	159.16
157	161.72
173	165.21
183	168.21

CROSS SECTION KM 1101.82

DESCRIPTION: This cross section is 1.5 km U/S of the Caboose. The left bank is treed from 0.0 m to 8 m. From 8 m to 15 m the bank has willows beyond which it is grassed to the water level. The right bank is gravel from the water level to 141 m after which the bank is grassed, with some small willows. The trees start at 175 m. The bed material had a D_{50} of about 100 to 120 mm with larger boulders present. the water level on the day of survey July 10, 1987, was 159.16 m.

TBM: Spike in tree on the top to the left bank, at 3 m on the cross section. Elevation - 169.351 m.

Figure C.7. Cross section km 1101.82



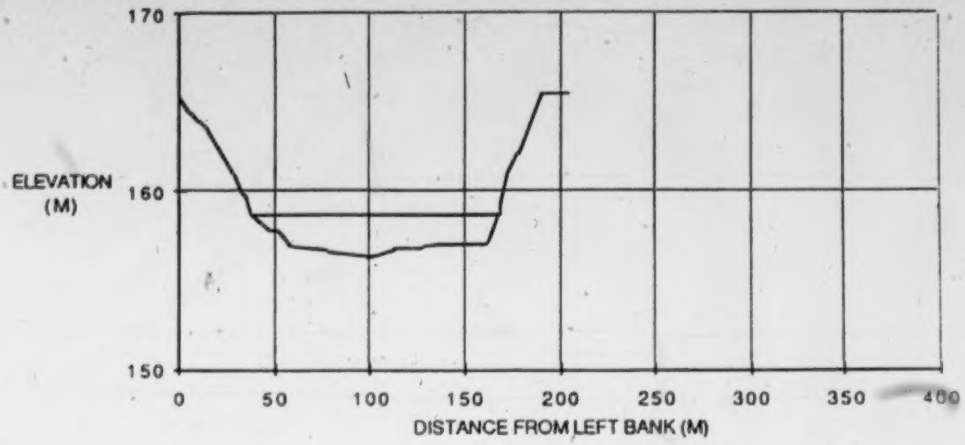
DISTANCE FROM LEFT BANK (M)	ELEVATION (M)
0	169.4
6	169.12
12	167.97
26	167.76
34.5	164.81
40.5	163.46
47	162.62
53	161.54
64.6	159.75
68.2	158.92
78	157.29
83	157.6
88	156.99
108	156.79
120	156.38
128	156.89
132	156.9
148	155.97
168	157.5
178	158.92
182	159.91
189	161.29
195	162.5
204	165.33
207	165.97
213	166.83

CROSS SECTION KM 1103.32

DESCRIPTION: This cross section is directly across from the Caboose. The left bank is grassed from 0.0 m to 35 m. From 35 m to the water level the bank is gravel with little growth on it. The right bank was gravel, but with much more grass growth. At 195 m small willows began and at 207 m poplars started. The bed material had a D_{50} of 100 mm. On the day of survey, July 10, 1987, the water level was 158.92 m.

TBM: Cut off post, north side of trail to river, at approximately 26 m on cross section. Elevation - 166.016 m.

Figure C.8. Cross section km 1103.32



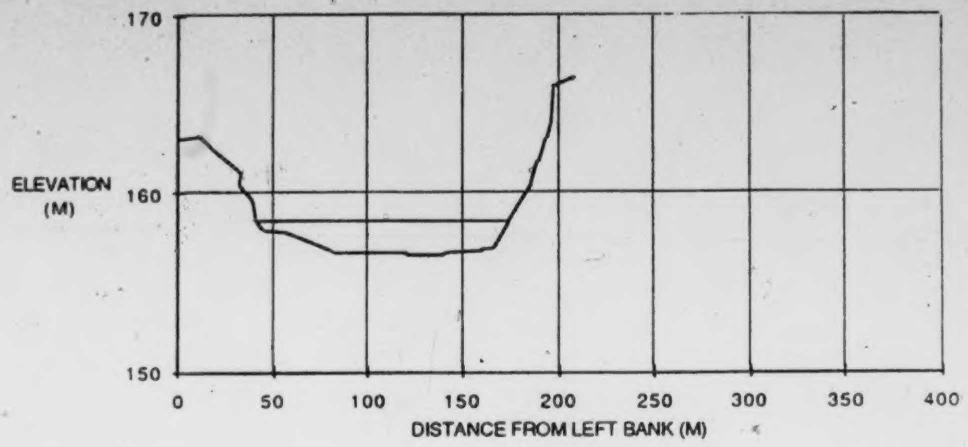
DISTANCE FROM LEFT BANK (M)	ELEVATION (M)
0	165.27
6	164.36
10	163.91
14.5	162.38
23.5	161.81
28.6	160.92
32	160.02
33.8	159.77
35.4	159.48
37.6	158.68
48	157.76
52	157.68
58	156.83
78	156.54
98	156.24
113	156.75
128	156.85
137	157.06
157	157.06
162	157.1
168	158.68
168.5	159.26
172	160.9
178	162.15
190	165.49
205	165.5

CROSS SECTION KM 1104.05

DESCRIPTION: This cross section is 700 m D/S of the Caboose. The left bank contains poplar up to 14.5 m, after which the bank is covered with willows up to 24 m. The bank is then grassed to the water level. The right bank is grassed from the water level to 190 m, at which point the trees start. The estimated D_{50} of the bed material is 100 mm. The water level on the day of survey, July 10, 1987, was 158.68 m.

TBM: Spike in tree on the top of the left bank, at 0.0 m on the cross section. Elevation - 165.56 m.

Figure C.9. Cross section km 1104.05



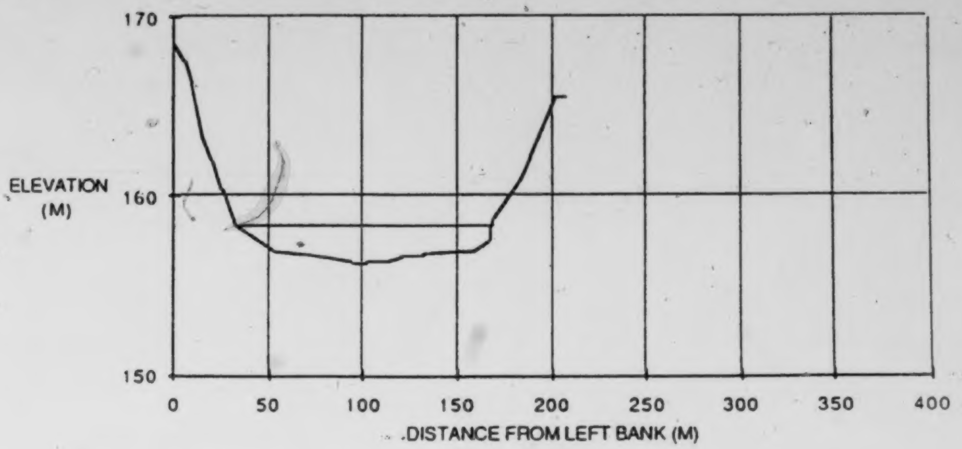
DISTANCE FROM LEFT BANK (M)	ELEVATION (M)
0	163.08
11	163.27
18	162.55
23.5	161.12
31.5	160.6
38	159.68
39.2	159.33
40.8	158.46
44.8	157.95
57	157.84
81	156.73
120	156.62
140	156.73
160	156.93
166	157.03
173.5	158.46
186	160.57
190	161.81
194	163.14
196.5	164.05
198	166.09
208	166.59

CROSS SECTION KM 1104.71

DESCRIPTION: This cross section is 1.4 km D/S of the Caboose. From 0.0 m to 11 m, the left bank is covered by poplar. Willows extend from 11 m to 38 m. The right bank is grassed from the water level up to 195 m where some willows start and at 198 m poplar growth begins. The bed material had a D50 of 70 -80 mm and a number of larger rocks were present, up to 500 mm in diameter. The water level on the day on survey, July 10, 1987, was 158.68 m.

TBM: Spike in tree on top of left bank, at 0.0 on the cross section. Elevation - 163.585 m.

Figure C.10. Cross section km 1104.71



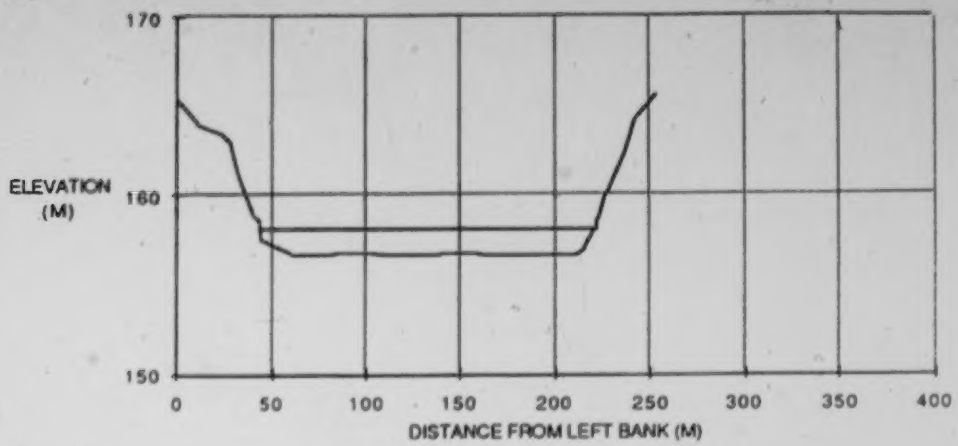
DISTANCE FROM LEFT BANK (M)	ELEVATION (M)
0	168.56
6	167.56
9.5	166.25
15	163.29
20	161.99
25	160.35
32.2	158.38
52.2	156.96
73	156.65
94	156.25
102	156.35
112	156.35
120	156.65
132	156.75
152	156.86
159	156.96
167	157.56
168	158.38
169	158.8
183	160.94
189	162.27
202	165.48
208	165.46

CROSS SECTION KM 1105.17

DESCRIPTION: This cross section is 2.7 km U/S of the East - West Channel split.The left bank is a steep slope with gravel and some grass present. The right bank is grassed with patches of gravel from the water level until 202 m at which point poplars begin. The bed material was estimated to have a D_{50} of 70 - 80 mm. Water level on the day of survey, July 9, 1987, was 158.38.

TBM: Hub in ground at 25 m on cross section. Elevation 160.440 m.

Figure C.11. Cross section km 1105.17



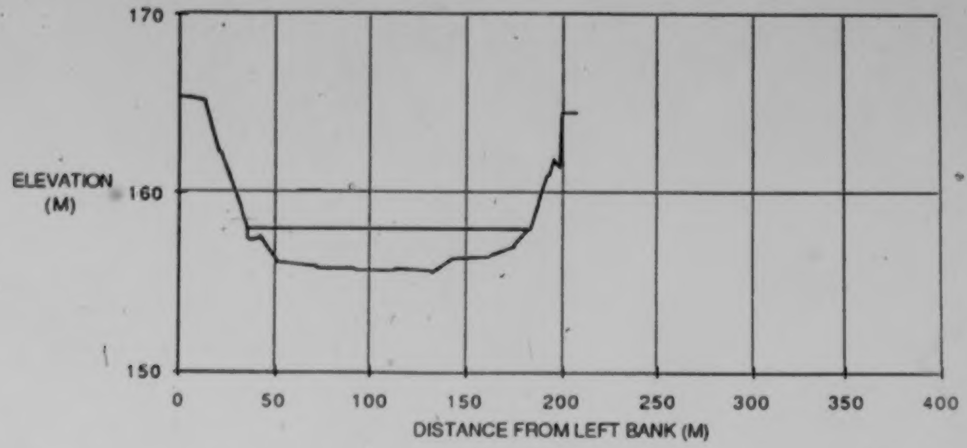
DISTANCE FROM LEFT BANK (M)	ELEVATION (M)
0	165.44
11	163.99
22	163.51
28	162.89
32.5	161.07
40	158.84
42.9	158.51
45	157.46
60	156.75
80	156.67
86	156.65
100	156.69
110	156.65
120	156.75
140	156.67
160	156.75
180	156.75
200	156.63
211	156.75
216	157.15
222	158.15
223	158.75
227	160.07
237	162.39
243	164.39
253	165.6

CROSS SECTION KM 1105.82

DESCRIPTION: This cross section is directly across from the tennis courts in New Town. The left bank is clear from 0.0 m to 32 m, beyond which tall grass and small willows extend to the water level. The right bank has a small cut bank at the water level after which the bank is grassed with small willows until 243 m, where poplar growth begins. The bed material is a gravel with a D_{50} of about 75 mm. On the day of survey, July 9, 1987, the water level was 158.15 m.

TBM: Hub in ground at 29 m on cross section. Elevation 162.604 m.

Figure C.12. Cross section km 1105.82



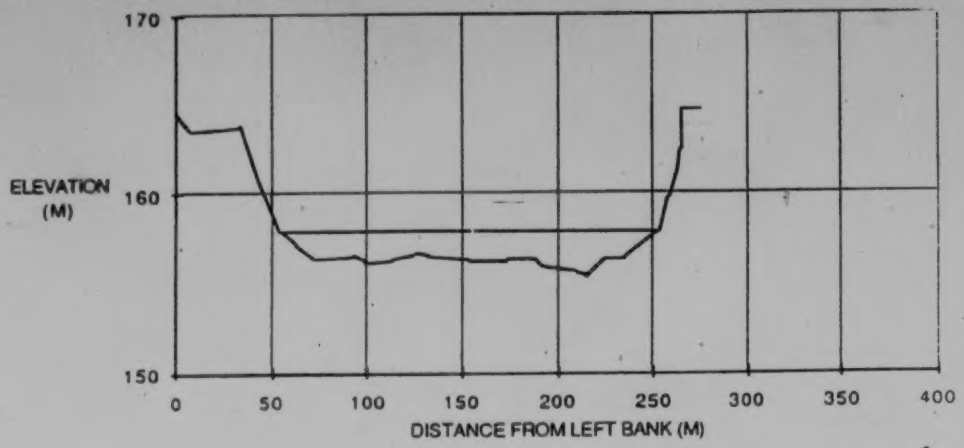
DISTANCE FROM LEFT BANK (M)	ELEVATION (M)
0	165.47
12	165.16
21	162.23
32	159.03
35.5	158
35.8	157.39
42	157.59
52	156.07
72	155.77
92	155.67
113	155.77
132	155.56
143	156.38
163	156.58
175	157.08
183	158
188	159.55
193	161.08
195.5	161.96
198	161.52
200	164.47
208	164.55

CROSS SECTION KM 1106.54

DESCRIPTION: This cross section is 1.4 km U/S of the East - West Channel split. The left bank is treed from 0.0 m to 13 m. From there to the water level the bank supports high grass with some small willows. The right bank is gravel, with some grass extending from the water level to 198 m, where there is a cut bank. Above this the bank is treed. The bed material was gravel with a D50 of 75 mm. The water level on the day of survey, July 9, 1987, was 158.00 m.

TBM: Hub in ground at 10 m on the cross section. Elevation - 165.312 m.

Figure C.13. Cross section km 1106.54



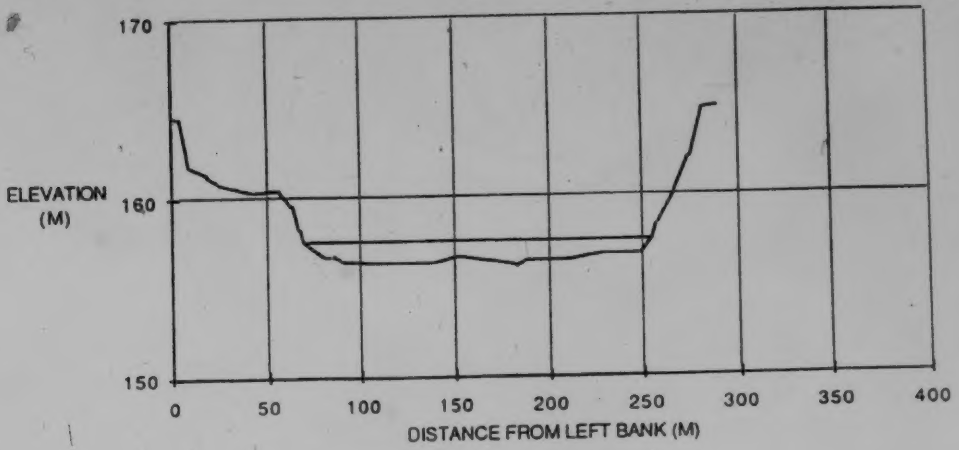
DISTANCE FROM LEFT BANK (M)	ELEVATION (M)
0	164.55
7	163.56
33	163.87
43	160.73
54	157.88
62	157.17
72	156.37
92	156.57
99	156.16
113	156.37
125	156.67
132	156.46
153	156.26
172	156.36
188	156.30
193	155.86
210	155.55
215	155.35
225	156.37
235	156.4
253	157.88
258	159.85
263	161.42
265	162.56
265.5	164.76
276	164.82

CROSS SECTION KM 1107.57

DESCRIPTION: This cross section is just U/S of the East - West Channel split. The far left bank is the edge of Riverview Drive. From 7 m to 43 m the land is covered by large trees and the steep portion of the left bank (43 m to 54 m) is grassed with a few small willows. The right bank is grassed from the water level to 265 (m). At this point a cutbank exists, above which tree growth begins. The bed material had a D_{50} of 75 mm. Water level on the day of survey, July 9, 1987, was 157.88 m.

TBM: Hub in ground at 42 m on cross section. Elevation 163.943 m.

Figure C.14. Cross section km 1107.57



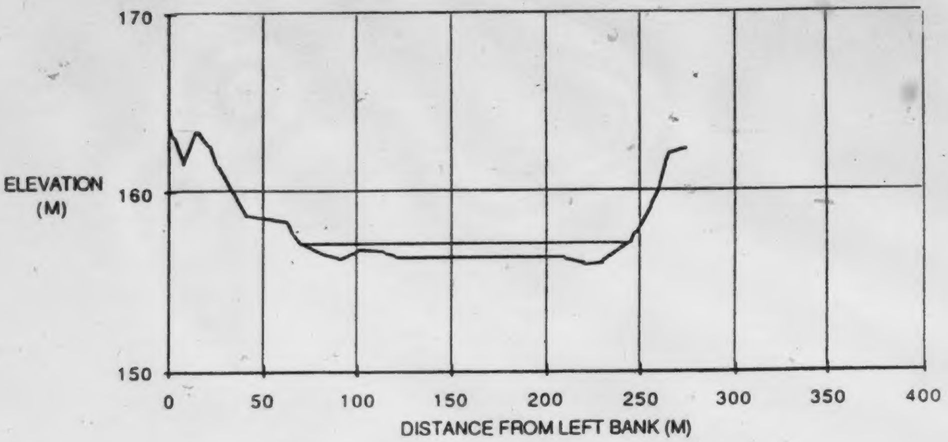
DISTANCE FROM LEFT BANK (M)	ELEVATION (M)
0	164.67
4	164.49
8.8	161.81
18.5	161.27
24.3	160.87
42	160.41
56	160.54
63	159.64
67	158.27
68.5	157.62
80.5	156.71
85	156.81
89	156.5
108.5	156.3
128.5	156.3
138	156.3
151	156.71
167	156.4
182	156.09
188	156.5
209	156.4
228.5	156.81
249	156.81
254.5	157.62
257	158.5
266.5	160.22
274.5	162.19
281.5	164.89
288.5	165.01

CROSS SECTION KM 1108.30 EAST CHANNEL

DESCRIPTION: This cross section is of the East Channel just D/S of the East-West Channel split. The left bank (0.0 m to 65 m) contains willows, tall grass, and a few small poplar. The right bank is quite steep with grass from 255 m to 281 m and poplar beyond. The bed material was gravel with a D_{50} of 70 mm. Water level on the day of survey, July 10, 1987, was 157.62.

TBM: Spike in tree on top of left bank, at 0.0 m on the cross section. Elevation - 164.21 m

Figure C.15. Cross section km 1108.30 East Channel



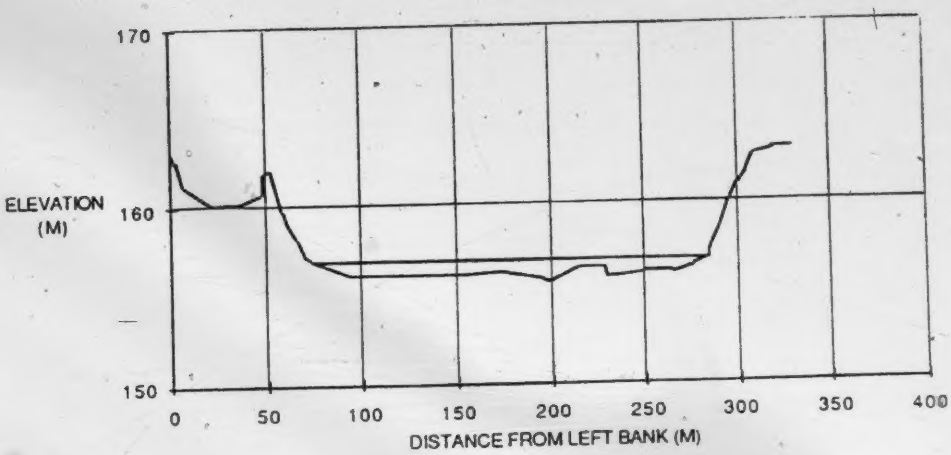
DISTANCE FROM LEFT BANK (M)	ELEVATION (M)
0	163.75
3	163.05
7.7	161.61
15	163.45
21	162.57
25	161.49
41	158.68
63	158.26
66	157.63
70	157.15
85	156.44
90	156.24
100	156.74
115	156.54
120	156.34
150	156.34
210	156.24
220	155.93
230	156.14
245	157.15
247.5	157.74
255	159.3
259.5	160.29
263	161.57
266	162.16
274	162.43

CROSS SECTION KM 1109.04 EAST CHANNEL

DESCRIPTION: This cross section is of the East Channel, 1.1 km D/S of the East - West Channel split. The far left of the section is the edge of the highway. A narrow band of poplar exists from 15 m to 21 m, beyond which willows and tall grass extend to the water level at 70 m. The right bank supports willows from the water to 266 m, beyond which poplar growth begins. The estimated bed material is gravel with a D50 of 50 to 70 mm. The water level on the day of survey, July 10, 1987, was 157.15 m.

TBM: Spike in telephone post on the left bank at 3 m on cross section. Elevation - 164.206 m.

Figure C.16. Cross section km 1109.04 East Channel



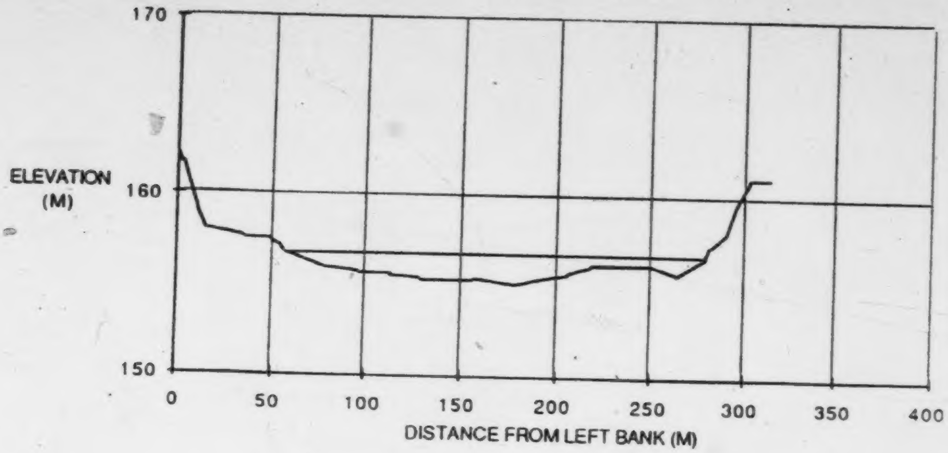
DISTANCE FROM LEFT BANK (M)	ELEVATION (M)
0	163.03
3	162.57
6.8	161.21
21.7	160.2
37.5	160.31
48.2	160.86
49	161.92
52	162.04
58.4	159.71
61	159.03
65.8	158.14
70	157.29
73.9	156.95
94	156.14
115	156.14
134	156.15
155	156.15
174	156.28
194	155.84
199	155.63
215	156.44
228	156.4
230	155.93
250	156.24
265	156.14
276	156.54
284	156.95
284.5	157.33
291	158.82
296	160.25
300	161.09
305	161.87
309	162.71
319	163.03
329	163.02

CROSS SECTION KM 1109.50 EAST CHANNEL

DESCRIPTION: This cross section is of the East Channel. The far left of the section (0.0 m) is the edge of the highway. A narrow strip of poplars are present from 49 m to 52 m and from 52 m to the water level the bank contains willows. Tall grass and willows extend from the water level to 309 m on the right bank with poplar beyond. Estimated bed material was gravel with a D_{50} of 50 - 70 mm. The water level was 156.95 on the day of survey, July 11, 1987.

TBM: Spike in telephone post #31 on east side of highway, left bank, at 2 m on the cross section. Elevation - 163.001 m.

Figure C.17. Cross section km 1109.50 East Channel



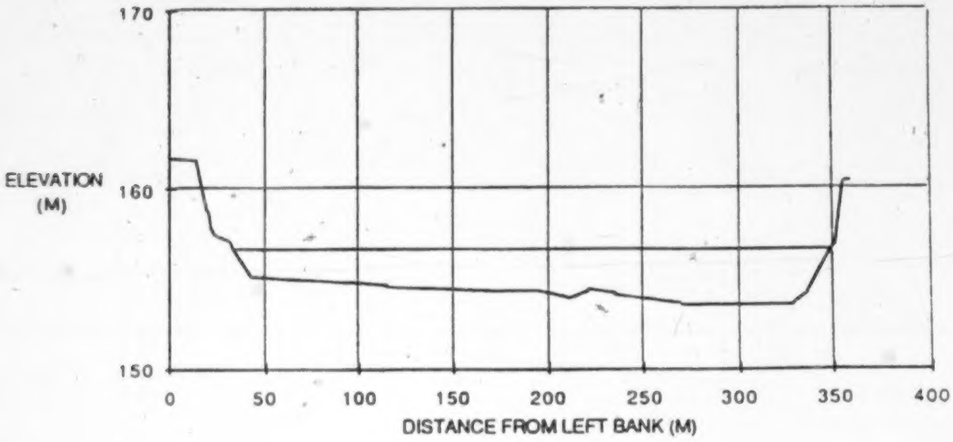
DISTANCE FROM LEFT BANK (M)	ELEVATION (M)
0	162.31
3	161.71
10.7	159.06
15.8	157.97
35	157.6
48.6	157.5
53.3	157.19
58.4	156.79
77	155.98
96	155.67
113	155.57
129	155.37
156	155.47
178	155.06
192	155.47
206	155.77
218	156.18
250	156.2
263	155.67
279.2	156.79
281.7	157.36
290.3	158.22
295.2	159.6
303	161.16
314	161.18

CROSS SECTION KM 1109.98 EAST CHANNEL

DESCRIPTION: This cross section is of the East Channel U/S of Island C-D. The far left bank (0.0 m) is the edge of the highway. Willows extend from the highway to the water level (50 m). Willows also extend from the water level (282 m) to 303 m on the right bank, with poplar beyond. The bed material is gravel , but the D_{50} was not determined. On the day of survey, July 11, 1987, the water level was 156.79 m.

TBM: Spike in third telephone post south of the railway crossing of the road, at 2 m on the cross section. Elevation - 162.193 m.

Figure C.18. Cross section km 1109.98 East Channel



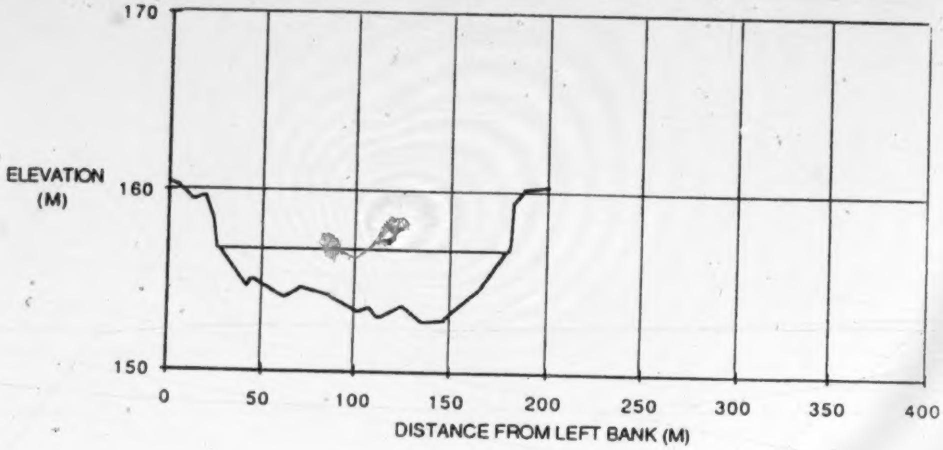
DISTANCE FROM LEFT BANK (M)	ELEVATION (M)
0	161.7
14	161.53
18.6	158.79
21.5	157.91
23.8	157.41
32.2	157.07
33.3	156.73
43	155.1
115	154.59
173	154.29
195	154.3
210	153.88
221	154.39
235	154.09
270	153.58
328	153.66
336	154.29
349	156.73
351	156.92
356	160.49
359	160.52

CROSS SECTION KM 1111.01 EAST CHANNEL

DESCRIPTION: This cross section is of the East Channel, about at the middle of Island C-D. The left bank is the grassy man made berm,, that surrounds Island C-D. A high cut bank is present on the right bank (355 m). The top of the cut bank is a grassed area which contains a number of houses. The bed material is gravel but a D_{50} was not determined. Water level of the day of survey, July 11, 1987, was 156.73 m.

TBM: Spike in tree on the left bank on the west side of the berm, at -5 m on the cross section. Elevation - 160.391 m.

Figure C.19. Cross section km 1111.01 East Channel



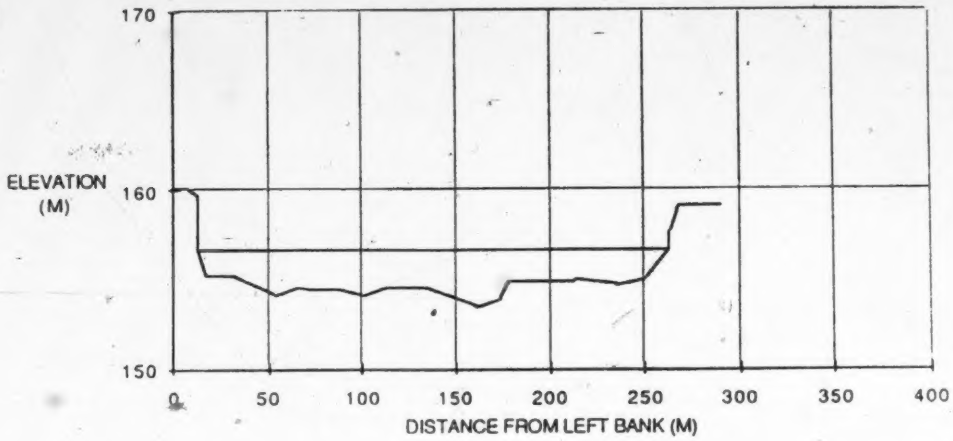
DISTANCE FROM LEFT BANK (M)	ELEVATION (M)
0	160.54
6	160.21
13	159.45
19.1	159.74
23.5	158.45
26.6	156.74
42	154.61
45	155.11
62	154.1
70	154.61
87	154.1
102	153.29
107	153.59
112	152.98
124	153.69
135	152.78
147	152.98
165	154.61
179.6	156.74
181.5	157.22
182.7	159.51
188.1	160.23
201	160.43

CROSS SECTION KM 1111.22 EAST CHANNEL

DESCRIPTION: This cross section is of the East Channel between the D/S end of Island C-D and the U/S end of Island B. The left bank consists of a man-made berm which is grassed. The right bank is Island B and has a high cut bank at 180 m. The top of the cut bank is heavily treed. Estimated bed material was a gravel with a D_{50} of 50 - 70 mm. Water level was 156.74 m on the day of survey, July 11, 1987.

TBM: Spike in tree on the left bank, at -6 m on the cross section. Elevation - 161.003 m.

Figure C.20. Cross section km 1111.22 East Channel



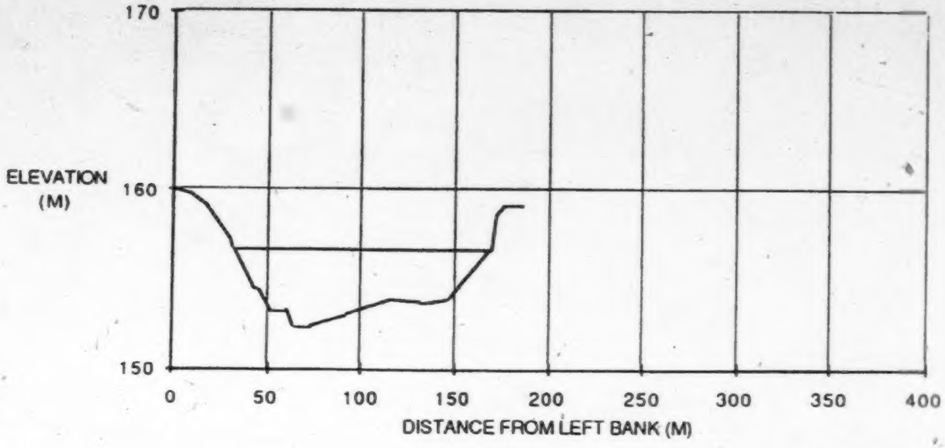
DISTANCE FROM LEFT BANK (M)	ELEVATION (M)
0	160.15
8	160.08
12.5	159.74
13	158.73
18	155.21
31	155.2
53	154.09
65	154.6
73	154.4
88	154.49
101	154.08
113	154.8
134	154.55
161	153.48
174	153.98
179	154.9
213	155
235	154.7
251	155.1
263	156.73
264	157.8
267.5	158.9
269	159.14
278	159.2
290	159.15

CROSS SECTION KM 1111.55 EAST CHANNEL

DESCRIPTION: This cross section is of the East Channel on the U/S end of Island B. The left bank is the east side of Island B which has a high cut bank at 13 m. The top of the left bank is treed with poplar. The right bank has a small cut bank above which it is heavily treed. The bed material was gravel but the D_{50} of the material was not determined. Water level was 156.73 m on the day of survey, July 11, 1987.

TBM: Spike in tree directly on top of the cut bank on the left bank, at 1 m on the cross section. Elevation - 161.01 m.

Figure C.21. Cross section km 1111.55 East Channel



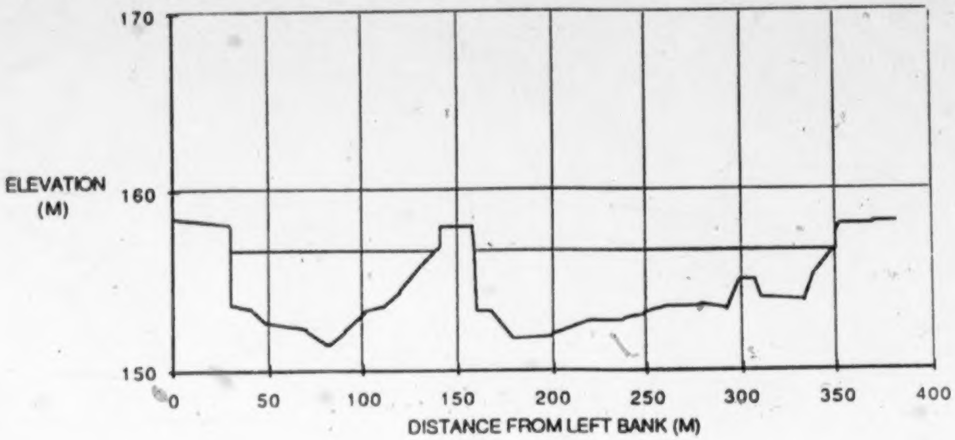
DISTANCE FROM LEFT BANK (M)	ELEVATION (M)
0	160.09
8.4	159.85
17	159.16
30.1	157.23
31.9	156.68
41.9	154.59
44.9	154.48
52	153.17
60	153.27
64	152.36
73	152.46
92	153.07
115	153.88
132	153.68
147	153.98
169.2	156.68
171.4	158.57
176.2	159.15
186	159.21

CROSS SECTION KM 1111.61 EAST CHANNEL

DESCRIPTION: This cross section is of the East Channel, immediately D/S of the Shell Bulk Station. The left bank is a graveled industrial area with a number of buildings along it. The right bank is the west side of Island B, which has a cut bank just above the water level (170 m). Above the cut bank is treed with large poplar. The estimated bed material was gravel with a D_{50} of 50 mm. Water level on the day of survey, July 11, 1987, was 156.68 m.

TBM: East-most angle iron on back of abandoned large boat on left bank, at 15 m on the cross section. Elevation - 161.043 m.

Figure C.22. Cross section km 1111.61 East Channel



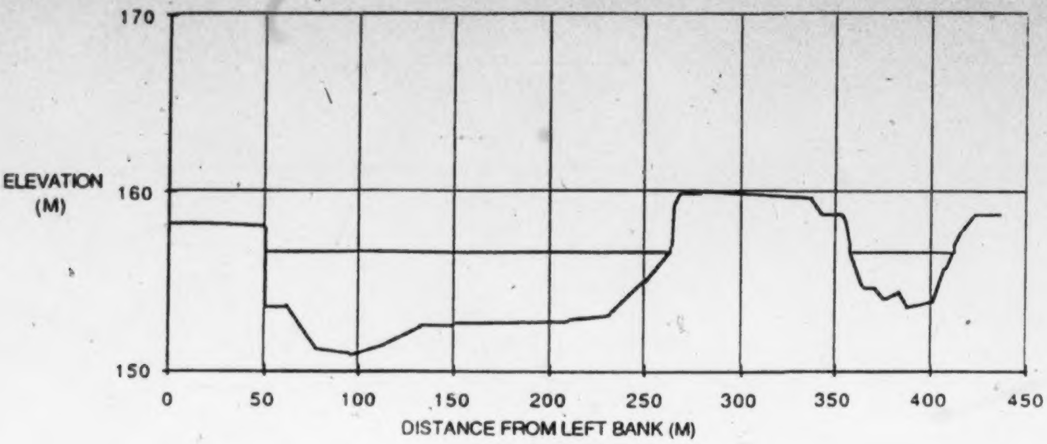
DISTANCE FROM LEFT BANK (M)	ELEVATION (M)
0.0	158.50
30.0	158.06
30.1	156.68
30.2	153.68
42.0	153.37
49.0	152.86
70.0	152.25
81.0	151.44
90.0	152.15
101.0	153.27
110.0	153.57
119.0	154.39
130.0	155.81
138.0	156.68
140.0	156.86
140.5	158.04
148.0	158.04
157.5	158.04
159	156.68
161	153.27
167	153.37
179	151.75
200	151.95
221	152.78
236	152.96
249	153.17
261	153.56
278	153.68
292	153.37
299	154.98
307	155.00
311	153.98
333	153.78
338	155.40
349.5	156.68
350	157.68
352.5	158.18
369.5	158.23
382	158.26

CROSS SECTION KM 1112.20 EAST CHANNEL

DESCRIPTION: This cross section is of the East Channel at the D/S end of Island B and cuts across the tip of the island. The left bank consists of a dock with its edge at 30 m, with a gravel yard to the left of the dock. The island at this section is covered with high grass. The far right bank is heavily treed from the water level (350 m) on upward. The bed material is gravel but the D_{50} of the material was not determined. On July 12, 1987, the water level was 156.68 m.

TBM: Top of bollard #7 on the left bank, at 29 m on the cross section. Elevation - 158.373 m.

Figure C.23. Cross section km 1112.20 East Channel



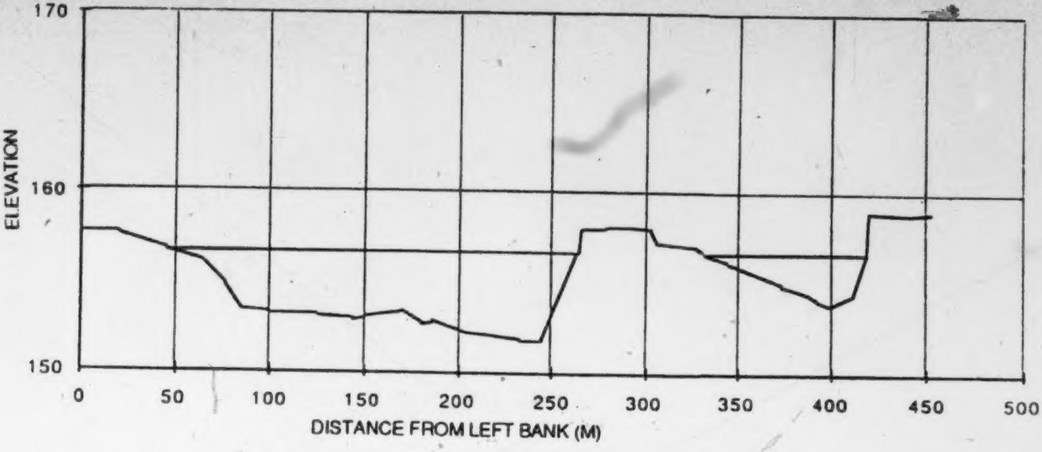
DISTANCE FROM LEFT BANK (M)	ELEVATION (M)
0	158.25
13	158.22
50	158.08
50.1	156.69
50.2	153.59
61	153.68
78	151.15
95	150.84
110	151.35
132	152.57
150	152.67
210	152.87
232	153.18
250	155
263	156.69
263.5	156.97
265.5	159.22
269	159.98
279	160.01
337	159.65
343	158.85
353	158.82
355.5	158.33
357.8	157.09
358	156.69
365	154.7
370	154.71
376	153.99
383	154.4
388	153.59
402	153.99
408	155.82
412	156.69
412.3	157.13
416.5	157.91
424	158.82
428	158.9

CROSS SECTION KM 1112.36 EAST CHANNEL

DESCRIPTION: This cross section is of the East Channel at the U/S end of Island A, just crossing the tip of the island. The left bank consists of a dock with its edge at 50 m, with a large graveled yard to the left of it. The island is heavily treed and the far right bank of the section is also heavily treed. The trees start almost immediately at the water (412 m). The D_{50} of the bed material was not determined but it was noted that it was gravel. Water level on July 12, 1987, the day of survey was 156.68 m.

TBM: Lip of dock on the SE corner of the dock, at 50 m on the cross section. Elevation - 158.092 m.

Figure C.24. Cross section km 1112.36 East Channel



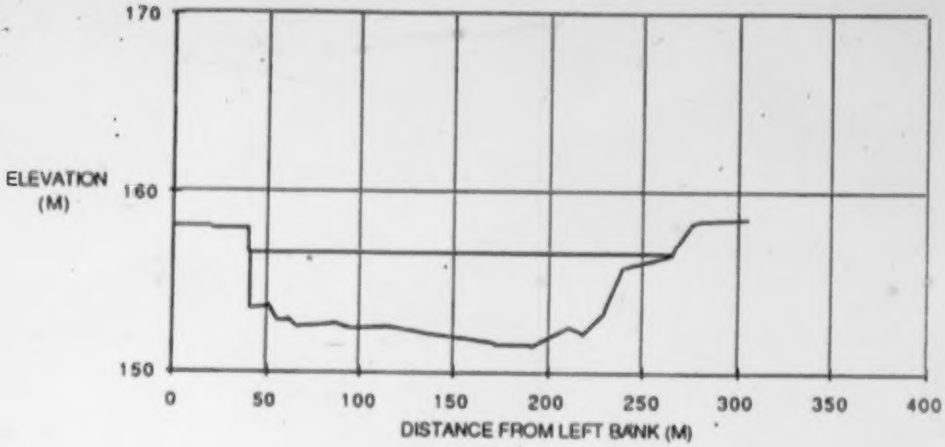
DISTANCE FROM LEFT BANK (M)	ELEVATION (M)
0	157.68
20	157.57
45	156.71
65	156.04
76	154.82
85	153.4
100	153.2
125	153.1
144	152.89
150	153.1
169	153.4
180	152.68
186	152.89
205	152.18
233	151.78
245	151.68
264	156.71
265.5	157.86
267.5	158.07
279	158.15
290	158.18
303	157.96
307	157.27
316	157.13
326	156.98
330	156.71
330	156.71
345	156.15
373	154.83
387	154.42
393	154.01
400	153.71
411	154.32
419	156.71
421	159.08
441	158.88
452	159.03

CROSS SECTION KM 1113.22 EAST CHANNEL

DESCRIPTION: This cross section is of the East Channel at the D/S end of Island A, just crossing the tip of the island. The left bank is at the ATL yards and consists of gravel, with no dock present. The island is heavily treed. The far right bank (420 m) is a cut bank with a large grassed area on the top. The bottom was rocky with an estimated D_{50} of 50 mm. On the day of survey, July 12, 1987, the water level was 156.70.

TBM: Top of bollard on the NE corner of Department of Public Works dock, at 40 m on the cross section and 40 m upstreamof the cross section. Elevation - 158.350 m.

Figure C.25. Cross section km 1113.22 East Channel



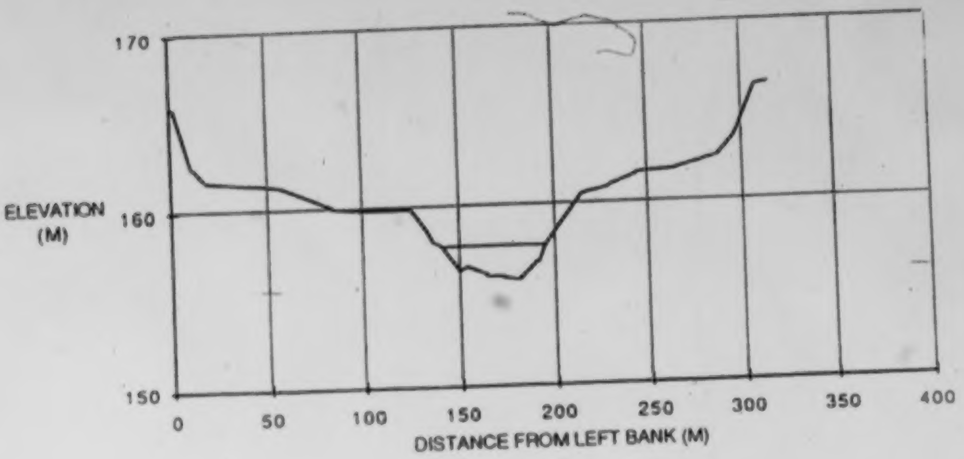
DISTANCE FROM LEFT BANK (M)	ELEVATION (M)
0	158.15
20	158.08
39.9	158.05
40	156.7
40.1	153.58
50	153.78
56	152.88
61	152.98
65	152.57
85	152.78
95	152.38
115	152.58
140	152.07
172	151.58
191	151.46
210	152.48
218	152.07
230	153.39
240	155.93
265	156.7
268	157.25
276	158.39
281	158.52
305	158.67

CROSS SECTION KM 1113.61 EAST CHANNEL

DESCRIPTION: This cross section is of the East Channel at the NTCL syncro-lift. The edge of the NTCL docks are at 39.9 m across the section with a flat gravel yard to the left of the docks . The right bank is just north of the Roman Catholic Mission in the Indian Village and is composed of sand. Small willows extend from the water level to 276 m, with poplar beyond. The bed material is gravel but because of the difficulty in obtaining a sample the D_{50} was not determined. Water level on the day of survey, July 12, 1987, was 156.70 m.

TBM: Top of bollard on the SE corner of syncro-lift, on the left bank, at 35 m on the cross section. Elevation - 158.369 m.

Figure C.26. Cross section km 1113.61 East Channel



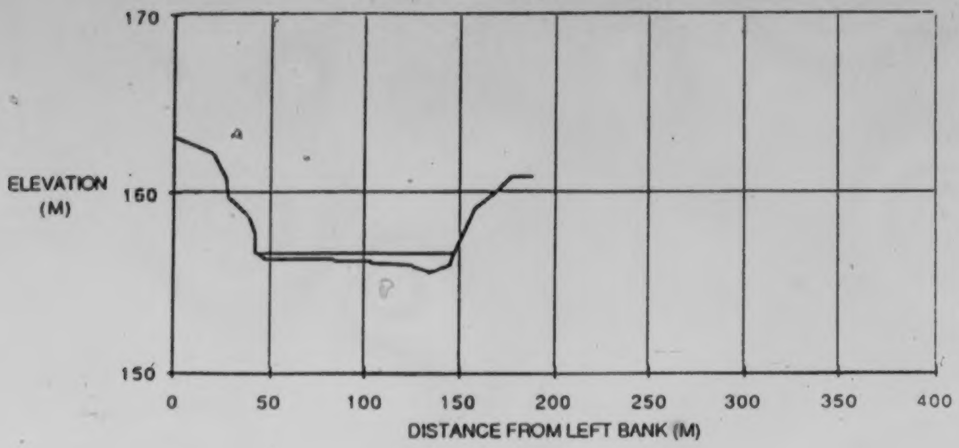
DISTANCE FROM LEFT BANK (M)	ELEVATION (M)
0	166.028
3.8	165.87
11.2	162.47
17.8	161.72
53.7	161.34
84	160.05
101	159.91
125	159.84
133	158.66
137	157.98
140	157.79
149	156.47
153	156.67
164	156.16
173	156.06
181	155.86
181.5	156.88
186	157.79
215	160.63
229	161.07
243.4	161.68
263	161.79
286.2	162.48
296.4	163.61
306.3	165.97
309.4	166.44
315	166.61

CROSS SECTION KM 1107.73 WEST CHANNEL

DESCRIPTION: This cross section is of the West Channel, just U/S of the West Channel bridge. The far left of the section (0.0 m) is the edge of Riverview Drive. The left bank is covered with willows and small poplars from 10 m to the water level. The right bank is grassed from the water level to 215 m after which willows start. The top of the right bank (306 m) is a graveled parking area. The bed material is gravel but the D_{50} was not determined. The water level on the day of survey, July 10, 1987, was 157.79 m.

TBM: Hub in ground very top of left bank, at 1 m on the cross section. Elevation 166.098 m.

Figure C.27. Cross section km 1107.73 West Channel



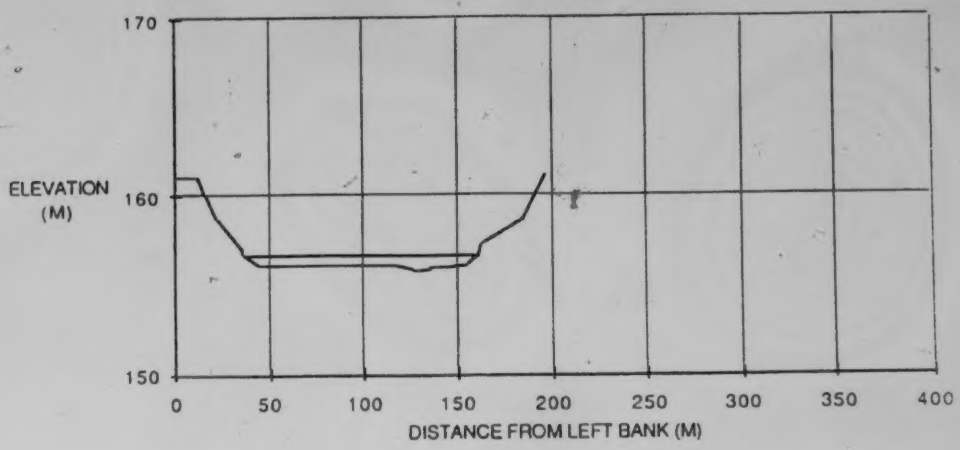
DISTANCE FROM LEFT BANK (M)	ELEVATION (M)
0	163.15
20	162.22
27	160.83
29	159.67
38	158.66
41.8	157.71
42	157.74
42.7	156.7
47.2	156.29
83	156.19
103	156.09
125	155.88
133	155.58
145	156.09
147.2	156.7
158	159.19
169	160.19
177	160.89
188	161.07

CROSS SECTION KM 1109.74 WEST CHANNEL

DESCRIPTION: This cross section is of the West Channel, 1.8 km D/S of the East - West Channel split. The left bank is treed from 0.0 m to 20 m, with grass from there to the water level. The right bank is grassed from the water level all the way up. No trees are present on this bank since the top is the airport runway. The bed material is gravel but the D50 was not determined. Water level on the day of survey, July 16, 1987, was 156.70 m.

TBM: Spike in tree on the top of the left bank at NE edge of the clearing, at 0.0 m on the cross section. Elevation - 163.745 m.

Figure C.28. Cross section km 1109.74 West Channel



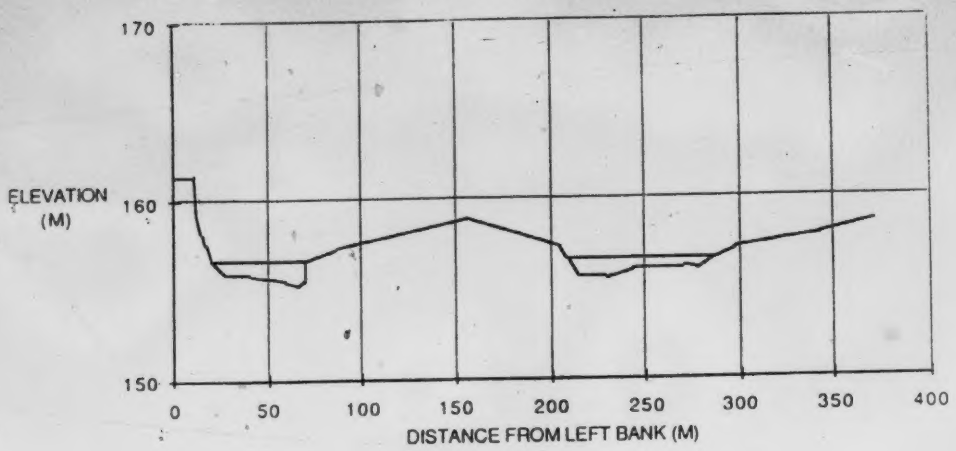
DISTANCE FROM LEFT BANK (M)	ELEVATION (M)
0	161.09
12	161.03
16	160.02
22	158.73
35	157.02
36	156.7
44	156.1
116	156.13
126	155.79
135	155.99
146	156.05
155	156.18
161	156.7
162.5	157.33
184.5	158.74
196.5	161.22
	158.57
	159.15
	159.21

CROSS SECTION KM 1110.49 WEST CHANNEL

DESCRIPTION: This cross section is of the West Channel, just upstream of the island. The left bank is treed up to 12 m, after which tall grass extends to the water level. The right bank is grassed from the water level on up. The top of the right bank is a grassed field, part of the Hay River airport. The bed material was rocky with an estimated D_{50} of 100 mm. The water level on the day of survey, July 16, 1987, was 156.70 m.

TBM: Spike in tree on the top of left bank, at 0.0 m on the cross section. Elevation - 161.87 m.

Figure C.29. Cross section km 1110.49 West Channel



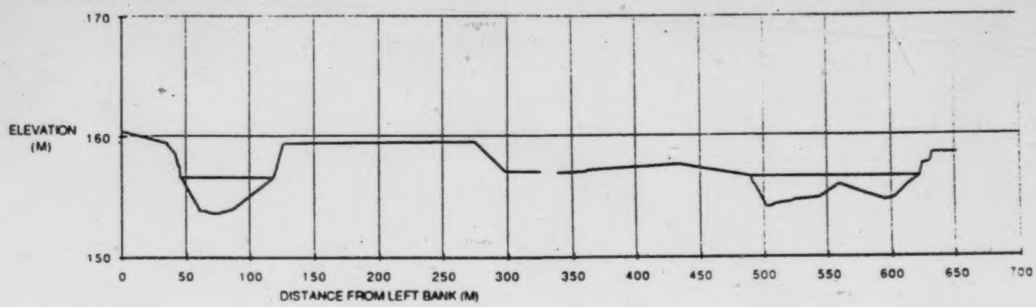
DISTANCE FROM LEFT BANK (M)	ELEVATION (M)
0	161.39
10	161.48
12	159.27
15	158.15
17	157.56
19.5	156.69
28	155.87
40	155.77
58	155.47
65	155.27
70	155.67
71	156.69
87	157.31
156	158.93
205	157.27
209	156.69
215	155.67
229	155.57
244	156.08
270	156.18
277	155.98
287	156.69
297	157.22
347	157.92
344	158.07
370	158.81

CROSS SECTION KM 1110.75 WEST CHANNEL

DESCRIPTION: This cross section is of the West Channel. It is just downstream of the split of the Rudd Channel. The left bank is treed up to 10 m, at which point a high cut bank exsists. The island contains high grass and some small willow at this section. The far right bank is a grassed field which is part of the airport. The bed material is gravel with a D_{50} of 100 mm. Water level on the day of survey, July 16, 1987 was 156.70 m.

TBM: Spike in tree top of left bank, at 0.0 m on the cross section. Elevation - 161.89 m.

Figure C.30. Cross section km 1110.75 West Channel

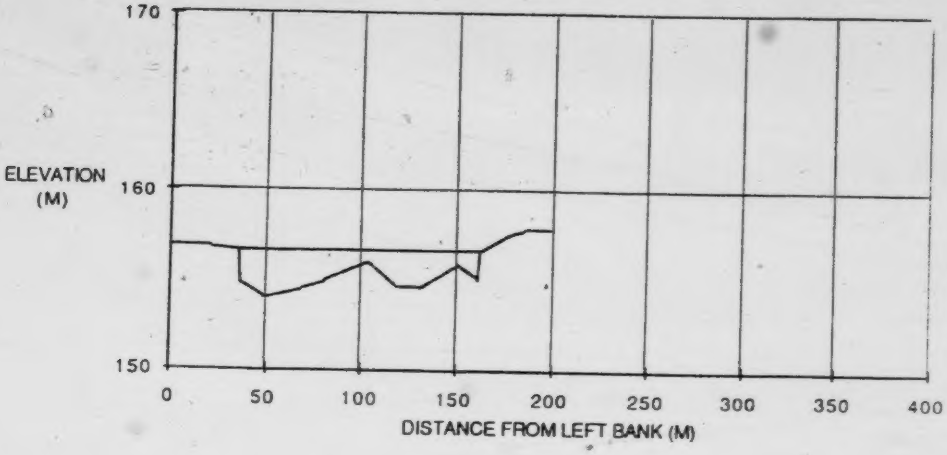


DISTANCE FROM LEFT BANK (M)	ELEVATION (M)
0	160.44
35.5	159.35
42	158.51
45	157.59
45.5	156.67
59.5	153.92
65.5	153.82
74	153.61
86	154.02
117.5	156.67
120.5	157.37
126.5	159.46
140	159.52
275	159.65
299	157.12
338	157.06
361	157.2
433	157.71
490	156.67
493	155.96
502.6	154.13
508	154.33
523	154.64
544	154.94
559	156.06
583	155.14
595	154.64
603	154.94
612	155.86
622	156.67
625	157.68
630	157.86
632	158.55
652	158.63

CROSS SECTION KM 1111.27 WEST CHANNEL

DESCRIPTION: This cross section is of the West Channel, 200 m from the mouth of the Rudd Channel. The left bank is grassed all the way down to the water level. The island is treed with small poplar from 125 m to 275 m after which it is grassed with a few small willows persisting up to 490 m. The far right bank is an earth bank with no vegetation on it. The bed material is gravel, but a D_{50} was not determined. The water level on the day of survey, July 16, 1987, was 156.68 m.

Figure C.31. Cross section km 1111.27 West Channel



DISTANCE FROM LEFT BANK (M)	ELEVATION (M)
0	156.86
13	156.88
21	156.84
35	156.68
37	154.74
48	154.03
68	154.54
80	154.95
103	155.96
118	154.64
130	154.54
150	155.86
161	155.04
163	156.68
177	157.63
185	157.91
198	158.01

CROSS SECTION KM 1112.07 WEST CHANNEL

DESCRIPTION: This cross section is of the West Channel just before it enters Great Slave Lake. The left bank is a marshy section of the island. The right bank is a grassy area which contains a number of residences. The bed material is gravel but the D50 was not determined. The water level on the day of survey, July 16, 1987, was 156.68 m.

TBM: Hub on right bank at 200 m on cross section. Elevation - 158.294 m.

Figure C.32. Cross section km 1112.07 West Channel

APPENDIX D

HISTORIC FLOOD DATA

AVAILABLE DATA

Prior to 1950 little flood data is available on Hay River, with the only sources being the diaries of the St. Peters Anglican and St. Anne's Roman Catholic Missions. This data is descriptive in nature, with only significant flood years warranting much more than a mention of the date that the river broke-up. Although the recorded history of Hay River dates back to 1868 there is no mention of flooding in the time period from 1868 to 1878. From 1894, when St. Peter's Mission began, a relatively continuous record of at least the dates of break-up exists for the East Channel. After 1950, spring break-up data is much more detailed with a number of years having a complete description of the break-up.

The available historical data indicates that significant flooding has occurred in: 1904, 11, 14, 34, 47, 51, 63, 74, and 1985.

CHRONOLOGICAL SUMMARY OF FLOOD OCCURRENCES

1894 - 1903

Records mention the dates of break-up but no significant flooding was recorded.

1904

On April 27 the ice began to break-up in front of St. Peter's Mission:

April 28 "By a.m. both banks and a great part of the mission clearing were under water and most of the village... But by two o'clock in Gods Goodness the water began to subside".

From St. Anne's Mission:

"Break-up 27th - 28th May, great flood, broke fence, covered field to a few steps from house, but some water in cellar. The point flooded to cemetery".

High water elevation was taken as 159.1 m, the elevation of the ground in front of the steps of the house at St. Anne's Mission.

1905 - 1910

Records only contain dates of break-up.

1911

At St. Peter's Anglican Mission

May 3: "At 10:30 p.m. the ice in the river began to show signs of going out. Later, it broke up and caused us a good deal of anxiety as it overflowed the bank in some places causing some of our skiffs to float..."

High water elevation at Mission was taken as 158.6 m, the elevation of the banks.

1912 - 1913

Both of these years were recorded as especially mild with descriptions indicating a thermal break-up.

1914

Ice began to push on April 30th, with break-up starting early May 1st. At the Anglican mission:

"May 1: It came into the Mission house, the floors of the dining room, kitchen and girls play room were flooded halfway across.... Water reached the stable and then receded. Water in a menacing condition all day.

May 2: Ice moved out this p.m. and all danger is now past."

At the Catholic Mission:

" Church full of water to above floor, water and ice round house."

The high water elevation was estimated at an elevation of 159.8 m, based on the elevation of the floor of the Catholic floor and the ground elevation of the stable area at the Anglican Mission.

1915-1922

No flooding was recorded in this period. In 1918, there is a mention in the Catholic Mission Diary of ice going out on the West Channel. "Ice block upstream of the island, May 7th and ice went out from West Channel... Ice went out peacefully at Mission on 9th May"

1923

At the Anglican Mission:

"April 29: Hunters report ice gone out of other branch of river.

May 1: About 4 p.m. ice broke up in the river and water overflowed the banks... Water remains over the banks on potato grounds.

May 4: River still up even with the banks.

May 7: River has dropped this p.m. and all danger of the flood is past."

High water elevation was taken as 158.8 m, based on the ground elevation of the potato field.

1924-1931

No flooding was recorded in this period.

1932

At the Anglican Mission:

"May 2: The ice began to move in the river. It blocked just above barracks.

May 3: The water rose to the top of our banks here today due to a jam at the mouth... The main river is nearly cleared now by 10 p.m.."

High water elevation estimated at 158.5 m, the top of the banks at the Mission.

1933

At the Anglican Mission:

"May 9: The ice in this river began to move from above Mission Island sometime before 4 p.m.... The river rose over two feet so that Mission Island and Vale Island were partly covered."

High water elevation estimated at 158.5 m, the elevation that would cause Mission Island to be partly covered.

1934

At the Anglican Mission:

"May 2: The main river began to move after midnight... the water was rushing like a rapid over the bank into the field. The water at the corral division was knee high."

The elevation of the high water was estimated at 158.8 m, which would correspond with knee high water at the corral.

1935 - 1946

No flooding was recorded.

1947

Fills "A", "B", "C", and "D" were placed in the fall of 1946 at the locations shown in Figure D.1. It was not until the summer of 1947 that they were raised to their design heights. "It will be understood that these fills were merely built to a height and width sufficient to allow machinery and motor vehicles to cross and were in all cases much lower than they were finally built" (Douglas,1954)

Water levels over-topped these fills early in the break-up. Water levels were high during break-up but no significant flooding took place as no permanent building received any flood damage (Douglas, 1954).

At the Catholic Mission:

> " Moderate scare at Mission, with water halfway to house... No noteworthy damage at Mission however, and the break-up was relatively uneventful."

A profile of high water levels are included in Figure D.1. This figure includes profiles for 1947, 1951, 1956 and 1963. These profiles were obtained from the reports by Stanley Grimble and Roblin (1959 and 1963). Peak levels at the East-West Channel split were 161.6 m and at the mouth of the East Channel 158.9 m.

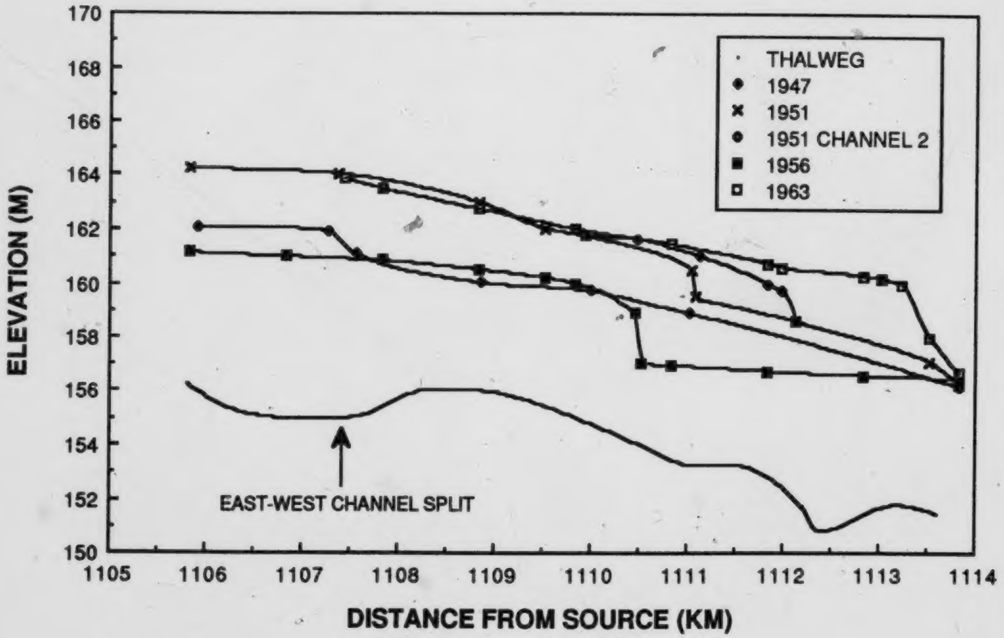


Figure E.1 - Historic flood level profiles

1948-1949

No flooding was experienced in these periods. Fill "D" (across the West Channel) was at an elevation of 163.9 m and was not overtopped at any time in these years. In this period blasting of the ice was done to minimize flooding. Exact location of the blasting in 1948 was not recorded, but in 1949 the ice was blasted from km 1108.8 to km 1111.0 in the East Channel (Douglas, 1954).

1950

No significant flooding took place in this year but a detailed account of break-up was recorded in a "Memorandum for the Chief" by Bruce Douglas (1951). Blasting operations began on April 21 and continued to April 25 when flow increased considerably. A double row of blast holes were completed from km 1108.8 (near Fill "C") to km 1111.0 (close to the upstream end of Island B).

At midnight May 2 the first rush of ice came, breaking ice to km 1111.0, where the toe of the jam was formed. Fill "D" had a 4' free board (water elevation 162.68 m), and at Fill "B" the water level was 160.99 m. The jam remained in place until early May 7 when the river opened right through to the lake, but ice jammed again for about one hour at the mouth causing the water to rise and flood that section of the town between the mainstreet and the river (elevation 158.5 m).

The report also states that runoff was probably more than that of 1947.

1951

In 1951 no blasting prior to break-up was done. Break-up commenced on May 3rd, with ice breaking down to km 1110.7 (upstream of Island D). Water began to flow over the West Channel Fill "D" late May 4th. This was about the peak flood level in the airport vicinity. Water was flowing to a depth of 1.22 m over runway (Douglas, 1951).

By early morning on the 5th water was flowing over both river banks along the whole East Channel, from the Easr-West Channel split to the mouth of the East Channel. Water going over the airport was then flowing over the road to the Fishing Village over a length of some 3 km. Finally at about 3:30 a.m. May 6th a new rush of ice and water came down the river and it broke through to the lake and the river cleared.

Figure D.1 shows the profile of the high water levels. It can be seen in Figure D.1 that the toe was located some distance upstream of the mouth. As pointed out by Douglas (1951), this probably limited somewhat the flooding that could have occurred in the town: "This last move was the feared one as in other years the ice has always jammed at the lake. This was the jam which we wished the R.C.A.F. to stand by for and very lucky it did not happen. I believe every building in the settlement would have been flooded"

The peak water level at the East-West Channel split was taken as 164.0 m and that at the mouth of the East Channel to be 158.7 m. These were obtained from the profile from Stanley, Grimble, Roblin (1959).

1952

After the flooding of 1951 an extensive blasting program was undertaken in the spring of 1952. The East Channel was blasted right from km 1108.8 to the mouth, almost 5 km. Five pound charges were placed in 3 lines across the channel, with 75 feet from line to line and the holes 60 feet apart on each line. It was found as work progressed upstream that only 2.5 pound charges were needed. In total 700 holes were blasted.

The river began to break-up on April 25th. On April 27 the toe of the jam was just upstream of Island A (km 1112.4). At the East-West Channel split (Fill "D") the water reached a level of 162.8 m and at Fill "C" water reached an elevation of 161.6 m.

On April 28th this jam broke and the toe moved to the mouth of the East Channel. This caused minor flooding at the Hay River Hotel and Menzies Fish Company (near the mouth of the East Channel). From the comment about minor flooding at Menzies Fish Company it was estimated the water rose to 158.6 m. By the afternoon of the 28th the ice was completely out of the East Channel.

1953

Break-up in 1953 was very quiet. From the descriptions available it was probably a thermal break-up (EMO File): "April 29: River very low and rotted out clearing through this late evening"

The West Channel Fill "D" was lowered in the fall of 1952 as shown in Figure 4. Even at this low level water did not over flow it. The peak water level at the East-West Channel split was noted to be 5.5 ft (1.7 m) below the fill (MacQuarrie, 1954). This is equivalent to an elevation of 158.2 m.

1954

Prior to break-up the East Channel was blasted from the upstream end of Island B (km 1111.5) to the mouth. Break-up began on the night of May 11-12 when the stage at the West Channel fill increased by 2.75 m (Ross, 1954). This increase in stage broke the ice up to the upstream end of Island B (km 1111.5), where the toe of a jam formed. During the night of May 12-13 the river rose another 2.4 m at Fill "D" and reached a peak of 161.9 m, at which point 2.1 m of water was flowing over the fill. This water level remained relatively constant to May 15. During this period the toe of the jam remained in the East Channel. On the 16th the river began to clear; "the ice was reduced in volume by breaking and melting to about a quarter mile in length at the mouth of the river"

The West Channel fill was completely washed out. The first rush of water after the fill was over-topped fanned ice and water over the lake ice at the mouth of the West Channel, due to the latter being frozen to the shore and bottom (Ross, 1954). A cross section was taken on the West Channel approximately 400 m downstream of the fill on May 14. Surface floats were placed on the water and were observed travelling at 1.9 m/s. Ross (1954) estimated a discharge of 453 m^3/s in the West Channel by assuming actual velocity was 80% of surface velocity, allowing for dead water and using the measured area of the channel. He also estimated the discharge in the East Channel was at least 700 m^3/s and could be as high as 1400 m^3/s. No actual measurements were done in the East Channel. No flooding occurred at the mouth of the East Channel.

1955

Little information could be found on break-up for this year. The only account was a letter by Miss E. Ramsey (1955), a school teacher at St. Peter's Mission: "The water went over the fill on May 1st and washed the highway out taking most the ice out the West Channel. The ice broke at the mouth in front of the Mission May 5th and was all clear by the next morning. There was no flood water at all on the Island"

Water levels at the fill must have been higher than 159.8 m, the height of the fill.

1956

In 1956 a blasting program was started in late April. The East Channel was blasted from the downstream tip of Island B (km 1112.2) to the DPW docks (km 1113.3). Because of warm weather blasting of the rest of the channel to the mouth could not be completed but the lake ice was blasted in a fan shape at the mouth (Harriot, 1956).

During the night of May 2-3 river ice broke up to km 1108.9. It was observed that on May 3 no ice was left on the river from Alexandra Falls to the jam in the town. On the 4th and 5th little change occurred in the conditions. On May 6 the jam pushed and a new toe was formed at the middle on Island D (km 1111.0). With the toe moving downstream the West Channel Fill "D" was over topped and reached a maximum of 160.9 m. The toe of the jam remained at km 1111.0 with the pack slowly melting in place. It was not until May 13 that the river was completely free of ice. A profile of peak flood levels were contained in the Stanley, Grimble, Roblin Ltd (1959) and are shown in Figure D.1.

From this profile peak levels were obtained for the East-West Channel split and near the mouth of the East Channel and are 161.0 m and 156.8 m respectively.

1957

Water began to flow over Fill "D" early April 29. Ice broke in the East Channel down to the downstream end of Island D where the toe of the jam formed. On May 3 blasting was done on the solid ice below the toe, from km 1112.4 to the mouth of the channel. Water levels at Fill "D" reached a peak on May 3 with a level of 161.1 m . This elevation was obtained from the description that water was flowing over the fill at a depth of approximately 8 ft (2.4 m) (Report for Spring Break-up, 1957 (Department of Highways)).

On May 5 some minor flooding occurred in the West Channel. Late on May 6 the jam in the East Channel began to move down stream. Water just reached the road at Royal Canadian Corp. Of Signals corner (km 1112.4), an elevation of 158.7. By May 7 the river was clear.

1958

Much work was done in 1958 prior to break-up. A pressure ridge had formed 800 m to 1200 m offshore opposite the West Channel. This ridge was about 3.7 m high and ran parallel to the shore (Harriot, 1958). It was blasted along with the East Channel. In the East Channel a 9 m wide strip was blasted from (km 1111.0) to the mouth.

On April 22 water began to rise and by midnight a jam had formed at the mouth of the West Channel, but no flooding occurred in that area. Early on the 23rd the discharge dropped, probably because of an upstream jam (Harriot, 1958).

In the afternoon a large surge of ice and water arrived in Hay River, breaking the jam in the West Channel and moving the ice out into the lake. This surge also broke up the East Channel to the downstream end of Island D where a jam formed. The toe stayed in this location until April 30 when the ice moved out into the lake. No flooding occurred in East Channel.

1959

Break-up was very mild with no water going over the West Channel fill (EMO Files) The blasting program was apparently quite extensive but little specific information could be found (Stanley, Grimble, Roblin Ltd, 1959).

1960

Break-up started on April 24 with the water levels going over Fill "D". The river was completely clear by May 1 (EMO File). No mention of significant flooding could be found.

1961

Ice and water began to spill over Fill "D" on May 8. By May 12 the river was clear of ice (EMO File).

1962

Little information available on break-up. River clear of ice between May 16-18 (EMO File).

1963

Little information could be found on the progression of break-up; most records concentrated on the effects of the flooding of the Town. On April 27 water levels began to increase with water running over Fill "D" at 1930 hours. A jam formed in the East Channel in the area of Island D. Flooding started early on April 30 when the jam moved downstream and the toe lodged at the mouth of the East Channel. At 4:00 pm on April 30 a jam 35 km upstream broke sending a surge downstream. This surge hit Hay River about 7:40 am on May 1 creating the peak levels. The high water level profile from Stanley Grimble Roblin Ltd. (1963) is shown in Figure D.1. This profile was used for flood levels at the three sites. Peak levels for the East-West Channel split and near the mouth of the East Channel were 164.0 m and 160.8 m respectively.

Although Fill "D" was washed out, little flooding occurred in the West Channel.

1964

Break-up was relatively quiet in 1964. Flood control measures were taken prior to break-up and included plowing snow off the river ice and blasting. The West Channel fill was also removed as the bridge was now complete across the channel. Break-up began on April 28 and by April 30 ice had pushed out the West Channel and into the lake. It was not until May 10 that the river was completely clear of ice (EMO

Files). Most accounts attribute the lack of problems to the lower than normal run-off.

1965

Blasting was done prior to break-up along the river and for 500 m out into the lake. A reconnaissance flight on April 24 revealed that the river was still frozen south of the border although north of the border the river was beginning to break-up (Town Flood Watch, 1965). On April 23 the river began to break-up in the town and push down the West Channel, where it stalled at the mouth. In the East Channel a jam formed at km 1111.15 (downstream of Island D). This jam moved downstream on May 2, forming a toe at approximately in the middle of Island B, km 1112.2 . Ice completely cleared the river on the evening of May 4. No significant flooding was reported.

1966

Break-up was extremely quiet. "Warm spring weather, with temperatures in the mid seventies helped to disintegrate the thin, rotten ice that remained on the surface of the river." (TAWPE, 1966)

Discharge was reported to be very low and ice was completely clear of the river by May 12.

1967

Early break-up patterns indicated that flooding was a good possibility (TAWPE, 1967). Above average snow depths existed in the basin, and the river and lake ice was thick with a heavy snow cover. Flood control measures included plowing the snow off the river and for a distance out into the lake. Blasting of the ice was also done in the East Channel from km 1110.0 out into the lake for a distance of 500 m.

By May 8 levels at Indian Cabins were reported to be up to the 1963 levels (TAWPE, 1967). Although discharge was very high in Hay River, the ice had deteriorated greatly by the time it arrived, so no flooding occurred. The river was completely clear by May 13.

1968

The East Channel was blasted prior to break-up as part of the flood control measures(TAWPE, 1968). By April 20 it was reported that the river was open for a distance below the Louise Falls. It was not until May 4 that the river was completely out. The ice at the mouth of the East Channel was the last to go as no push of water and ice came from upstream. The ice that did come was so slushy it simply ran under the intact ice at the mouth (TAWPE, 1968).

1969

The ice was very rotten by the time discharges started to increase. A jam formed in the East Channel on April 26-27, but the discharge was low so no high water was experienced (TAWPE, 1969). No blasting was done prior to break-up, but blasting was done in front of the jam that formed in the East Channel as high water was reported to the far south of the basin. The river went out on April 29, before any dramatic increase in discharge was experienced.

1970

No blasting was carried out this year. Instead the ice was perforated with 20" diameter holes put down on 20 foot centres (Town Flood Watch records, 1970). From the description it is believed that this was just done in the middle section of the East Channel. Break-up was very mild with levels below normal. The river was clear by May 7 (TAWPE, 1970).

1971

McBryan reported levels were the lowest since 1959 (TAWPE, 1971). Some sections of the East Channel simply rotted in place. The river was clear of ice by April 30 (TAWPE, 1971).

1972

Discharge was reported to be above normal at break-up (TAWPE, 1972). On May 5-6 both channels broke with some jamming occurring. This created some concern since a greater than normal discharge was reported in the south. By May 7 most of the jammed ice had moved out into the lake from both channels, so little flooding was experienced when the flood crest arrived on May 10. This crest carried some ice but as the ice was very deteriorated it did not jam. Some minor flooding took place as water went over the bank in the West Channel, an elevation of 158.6 m.

1973

No information could be found on the 1973 break-up, neither in the town flood reports nor the newspapers.

1974

In 1974 a number of flood reduction measures were undertaken. These included plowing and perforating the East and West Channels. A pressure ridge was present at the mouth of the West Channel and was closer to the shore than normal, with about 600 m of rough ice in front of it (Town Flood Watch records, 1974). Sections through the pressure ridge were cleared bu bulldozer to try to allow water to flow through it.

On April 27 ice started to move through the West Channel and jammed at the mouth. In the East Channel ice broke up to

Island D where the toe of the jam formed. A large jam was reported at Indian Cabins on the 28th. This jam broke on April 29 at 3:00 pm and a surge was sent downstream. On April 30 the surge hit Hay River, sending water over the banks at the New Indian Village on the East Channel (km 1110.8). This surge moved the toe of the jam downstream in the East Channel to about km 1112.25 (the downstream end of Island B) with water flowing over the Government Docks (km 1112.1) and reaching the highway at km 1112.2. Ice started to move in the West Channel on May 1 and flooding started to occur there. Despite the cleared sections ice and water could not get past the rough ice and the pressure ridge. On May 2 it was decided to blast the pressure ridge on the West Channel as water levels reached a peak of 159.3 m. This was a surveyed high water mark. The level was obtained from the 1:2000 flood risk map for Hay River. A peak water level of 162.2 m was also obtained at the East-West Channel split from the UMA (1979) report. After the blasting, water levels receded (TAWPE, 1974). In the East Channel the toe of the jam began to move downstream on May 3. As it moved water levels rose to the railroad track (elevation 158.6 m) at Carter's Float Plane Base (km 1112.5) (Town Flood Watch records, 1974). By May 4 at 7:00 am both channels were clear of ice.

1975

Break-up for this year was one of the quietest on record (TAWPE, 1975). The ice was completely out on May 1.

1976

The ice in both channels were perforated prior to break-up. With above normal temperatures, flooding was feared and so the ice was also blasted at the mouth of the West Channel (Town Flood Watch records, 1976). Break-up was complete by April 27 with no flooding occurring.

1977

Break-up in 1977 was very mild with the river all clear by May 4 (Hub, 1977). This break-up was monitored by UMA (1979). Water levels were recorded as part of this study. Water levels near the mouth of the East and West Channel were 156.9 m and 158.1 m respectively. At the East- West Channel split the peak level recorded was 161.1 m.

1978

The first push occurred on May 3 in both the East and West Channels. By May 4 the toe of the jam was at the upstream end of Island B (km 1111.5) (Town Flood Watch records, 1978). This caused water in the New Indian Village (km 1110.8) to over top the road. Later on the 4th the toe moved downstream to km 1112.2, sending water over the Government docks (km 1112.1). The water went up to the railroad at the docks (Hub, 1978), an elevation of 158.4 m. The river was completely clear of ice by May 7.

1979

Prior to break-up the ice on both channels was perforated (Town Flood Watch records, 1979). By May 10 the river had broken up to the NWT-Alberta border (Hub, 1979). On May 11 the West Channel broke and plugged at the mouth and on May 12 the East Channel broke to the upstream end of Island B (km 1111.5). A jam that had formed at Indian Cabins broke on May 13. The surge from the Indian Cabins jam cleared the West Channel on the 14th but not until water went over the banks at an elevation of 158.8 m. No flooding occurred in the East Channel although water levels reach to within 0.15 m of the docks (Town Flood Watch records, 1979) (elevation 157.9 m). A peak flood level at the East-West Channel split was estimated from a report in the TAWPE (1979) that water levels peaked at the West Channel bridge 16 ft (4.9 m) above the original ice level. The river was completely clear by the 15th.

1980

Break-up was mild with the river being clear by April 29 (Hub, 1980).

1981

Prior to break-up ice was reported to be thinner than normal (Hub, 1981). For the most part water levels were low with some minor flooding taking place at the New Indian Village (km 1110.8), an elevation of 160 m. A peak level was estimated at the East-West Channel split (elevation 161.9) from a photo in the Hub (1981). Ice was out by May 6.

1982

No flooding occurred in 1982 as flows were very low. Ice was out by May 11. A peak water level was estimated (elevation 160.4) from a photo in the Hub (1982).

1983

Ice broke at the West-East Channel split on April 28. Water levels were very low with ice going out May 3-5 (Hub 1983).

1984

Break-up again was very mild with ice being thinner than normal (Hub, 1984). Channels were all clear by April 24.

1985

Over the 1984-85 winter a pressure ridge was formed on the lake off the mouth of the West Channel. This ridge was closer to the mouth than normal, being about 400 m offshore, and was reported to be 2 to 4 m high (Wedel, 1988). No blasting or grading was done on this pressure ridge as had been done in past years.

Break-up began on April 28 at the WSC gauge site. On April 29, ice in the West Channel began to break-up, with not much occurring from then to May 4. During this time it was reported that ice and water was flowing over the bottom-fast ice at the mouth of the West Channel and was ponding at the base of the pressure ridge.

A large jam that had formed at Indian Cabins (km 920.63) was reported to have broken on May 5. The next day the ice on the East Channel began to move and a jam was formed at the downstream end of Island C-D. This jam caused extensive flooding of Island C-D. Early on May 7 a huge surge of water and ice was reported moving down the West Channel. This surge was thought to be the result of the Indian Cabins jam. Within 15 minutes the Fishing Village was flooded, with water reaching a depth of over 1 m on the roadway (an elevation of 159.9 m) (Underhill Engineering Ltd, 1985) During this flooding it was reported that ice and water was jamming against the pressure ridge at the mouth of the West Channel. By early May 8, water levels had lowered in the West Channel. Later on the 8th the toe of the jam in the East Channel moved to the mouth, but water levels downstream of Island C-D did not reach flood level. Ice was completely out by 4:00 am, May 9.

Underhill Engineering was contracted to document high water marks in Hay River. From this work peak flood level were obtained for the mouth of the East Channel and East-West Channel split. These were 1158.5 m and 163.5 m respectively.

1986

Prior to break-up it was reported that lake and river ice was thicker than normal. Because of the thick ice, blasting was done on the West Channel.

Ice began to move in the West Channel on May 2. In the East Channel the ice broke to the downstream end of Island C-D on the 4th. Later in the day the toe moved downstream a few hundred metres, stopping behind the Hay River Hotel (km 1111.7).

On May 5 a jam that had formed at Indian Cabins broke. On May 6 some flooding was reported at the New Indian Village (km 1111) as water reached the road. May 7 water levels reached a peak of 163.4 m at the West Channel Bridge and water went over the banks at the Fishing Village (elevation 158.95 m). In the East Channel some minor flooding occurred at km 1112.4, as water went over the docks, an elevation of 158.5 m (Town Flood Watch records, 1986).

McBryan summarized the 1986 break-up as a smaller version of 1985, the difference being a lower discharge. The river was completely clear by May 8.

1987

Prior to break-up considerable flood control works were done on the river. This included clearing the snow from the lower portions of the East and West Channels and a ditch witch was used to cut ice in the East Channel. In the West Channel snow dykes were built out onto the lake to constrain flow in the hope it would carry ice and water out away from the mouth.

Ice began to break-up at the townsite on April 26. A jam was formed in the West Channel just upstream of the mouth and in the East Channel ice jammed at the downstream end of Island C-D. A large jam at Indian Cabins gave way on the 27th.

Over the next few days little movement occurred. Ice from the jam at Indian Cabins (km 920.63) arrived on the 28th. This caused the head of the jam to grow upstream with little movement occurring at the toes. On the 29th and 30th the jam began to melt in place due to warm water coming from upstream. Ice began to move out into the lake on the 30th and by May 1st the river was free of ice.

Peak water levels at the mouths of the East and West Channels and the East-West Channel split were 158.2 m, 158.1 m and 162.2 m, respectively.

1988

Refer to Section 6.34 of the thesis.

Appendix E

Summary of field data

Distance from source (km)	Water elevations April 26 PM GSC (m)	Water elevations April 27 AM GSC (m)	Water elevations April 27 PM GSC (m)	Water elevations April 28 AM GSC (m)	Water elevations April 29 PM GSC (m)	Water elevations April 30 PM GSC (m)	Water elevations May. 1 AM GSC (m)
EAST AND MAIN CHANNELS							
1113.61							156.671
1112.356	156.698			156.877		156.877	156.715
1111.612				157.278		157.278	156.715
1111.428				159.793		159.793	
1111.16				159.99		159.99	
1110.92				160.115		160.115	
1110.46				160.314		160.314	
1110.262				160.56		160.56	
1109.98	159.334			161.078		161.078	157.18
1108.3	160.758			161.92		161.92	158.481
1105.49	161.98			163.087		163.087	159.232
1103.318				164.29		164.29	160.786
1098.264				165.393		165.393	161.745
1095.531	164.201			166.17		166.17	
1089.57	166.833			166.678		166.678	165.08
1086.388	167.617			167.028		167.028	166.22
WEST CHANNEL							
1111.266		157.294	157.692		157.743		156.73
1109.74		159.932	161.052		161.118		157.65
1108.146		160.683	161.729		161.584		158.114
1107.892		161.069	161.868		161.868		158.24

Table E.1 Summary of water levels, break-up, 1987

Distance from source (km)	Water elevations April 25. GSC (m)	Water elevations April 27. GSC (m)	Water elevations April 28. GSC (m)	Water elevations April 29. GSC (m)	Water elevations High Water GSC (m)
WATER LEVELS VIA EAST CHANNEL					
1112.36	156.55	156.68	156.73		
1111.61			156.76		
1111.43		156.79		156.73	
1111.16		156.83		156.78	
1110.92		157.3		157.12	157.36
1110.46		157.82		157.9	158.61
1109.98	157.18	160.02	160.05	159.83	160.38
1108.3	158.18	161.56	161.67	161.43	161.68
1105.49	158.67	162.34	162.44		
1103.318	159.22	163.53	163.64		
1098.26	162.38	164.08	165.01		
1095.53	162.38	164.47	165.42		
WATER LEVELS WEST CHANNEL					
1111.27	156.78	158.66	158.62	158.46	159.24
1109.74	157.61	160.05	160.01	159.79	160.48
1107.89	158.14	161.36	161.35	161.08	161.43

Table E.2 Summary of water levels, break-up, 1988

Table E.3 Data for bright sunshine, stage, and snow depth relation.

YEAR	DISCHARGE	ELEVATION AT E-W SPLIT (M)	FULLY DEVELOPED ELEVATION	RATIO MEASURED/ANALYTICAL	HOURS OF BRIGHT SUNSHINE WITH TEMP >-5.0	ACCUMULATED SNOWFALL (CM)
1974	680	162.15	161.40	1.16	199.9	138.5
1979	878	162.7	162.08	1.11	191.4	105
1981	790	161.9	161.77	1.03	218.8	111.5
1982	657	160.4	161.32	0.80	281.7	127.7
1985	1350	163.5	163.24	1.04	237.1	120.7
1986	900	163.4	162.11	1.24	222.7	171
1987	670	162.2	161.37	1.17	190	141